

Long-Term Research of Urban Ecosystems in Israel: Monitoring Socio-Ecological Dynamics and Wellness

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Summary

Urban areas, the fastest expanding biome, in which natural and semi-natural ecosystems are embedded, are highly impacted by anthropogenic activities. These ecosystems provide essential ecosystem services, and are crucial for biodiversity conservation, and consequently require long-term ecological and social monitoring, particularly in rapidly urbanizing regions like Israel. To carry out such an effort, our interdisciplinary team proposes establishing an urban Long-Term Ecological Research (LTER) program in Haifa (Mediterranean) and Be'er Sheva (hot-arid) to understand the complex interactions between ecological processes and human activities and their wellbeing in cities. The main goals include defining the baseline status of urban ecological systems by studying their biodiversity, climate, ecosystem services, and social aspects; and examine the relationships between these socio-ecological components to grasp their interactions. Further, we propose to study patterns and trends over time by analyzing spatial and temporal changes in these elements and human-nature relationships, leading to development of actionable policy recommendations to guide urban planning and conservation efforts. The program comprises of five interconnected work packages (WPs) that will monitor urban fauna, climate, vegetation, fungi symbionts of trees, and ecosystem services like pollination, flood regulation, air quality, and carbon uptake by trees. An additional significant focus is on social aspects, particularly cultural services and resident wellbeing, assessing how residents perceive and utilize urban green spaces and the associated ecosystems. Public engagement through citizen science initiatives will enhance data collection, increase public awareness, and involve residents in environmental issues, fostering a sustainable long-term monitoring network. The policy work package aims to convert scientific findings, to be gained through sophisticated analytics and predictive modelling, into practical recommendations for sustainable urban development. This will involve roundtable discussions with stakeholders and continuous engagement to ensure the recommendations are relevant to real-world challenges. This collaborative and multidisciplinary approach aims to promote resilience, enhance ecosystem services, and improve the quality of life for urban residents, serving as a model for other regions facing similar challenges. This initiative aligns with global trends towards urban sustainability and resilience where both human dimensions and ecosystem function are assimilated into the planning processes.

Introduction

Driven by land use and climatic changes, all ecosystems are continuously undergoing functional and structural modifications. **Urban areas, the fastest expanding biome, are highly impacted by human activities, making them crucial for biodiversity conservation, which necessitates long term monitoring** (1,2). Moreover, urban ecosystems, where most of humanity resides, are essential to understanding the interplay between human welfare and ecological processes, as well as their mutual impacts (3). This is particularly important in Israel, where rapid population growth and urbanization necessitates balancing development with nature protection (4,5), while enhancing urban residents' wellbeing. **Despite this need, Israel currently lacks a systematic monitoring scheme of urban ecosystems that integrates social and ecological complexities to produce a profound understanding and science-based recommendations regarding urban sustainability and biodiversity conservation.** Our interdisciplinary team, with expertise in ecology, sociology, climatology, and remote sensing, among others, aims to bridge this gap.

The Importance of Urban Ecology

Urban ecology examines how urbanization alters ecological processes and structures (6,7). Cities, heavily influenced by human activity, experience rapid environmental changes that impact biodiversity, nutrient cycling, hydrological processes, and climate regulation (8-10). **Monitoring and understanding these changes is essential**

for developing strategies to mitigate negative impacts and enhance urban resilience and sustainability. Key ecological drivers in urban areas include habitat fragmentation, pollution from multiple sources, abundance of invasive species, the urban heat island effect, and climate change. Habitat fragmentation isolates populations, reduces genetic diversity, and increases vulnerability to local extinctions (11). Pollution, particularly air and water contamination, threatens biodiversity in urban areas and their vicinity, affecting humans and species health and ecosystem functions (12). The urban heat island effect, where urban regions experience significantly higher temperatures than their rural surroundings, exacerbates stress on both wildlife and plant species, alters microclimates, and potentially shifts species distributions (13,14). Climate change compounds these impacts by altering temperature and precipitation patterns (15). Consequently, urban biodiversity is profoundly impacted (16,17), alongside the negative effects these processes have on human wellbeing (18).

Human interventions, such as urban planning and community engagement in conservation efforts, significantly shape urban biodiversity dynamics and human-nature relationship (19). Effective urban planning can enhance biodiversity and ecosystem services by creating green corridors and preserving natural habitats (20). Community engagement in conservation fosters a stronger connection between residents and their environment, promoting sustainable practices and enhancing urbanites quality of life (21,22). **Understanding and addressing these factors are essential for creating resilient urban ecosystems that benefit both nature and people** (23).

Urbanization in Israel

Israel is experiencing significant urban growth, with over 93% of its population living in urban areas as of 2022 and an annual 2% increase in urban population (24). Driven by population growth, economic development, and social factors, major cities like Jerusalem, Tel Aviv, Be'er Sheva, and Haifa have seen substantial population growth of 10%-30% from 2008 to 2022, while cities like Beit Shemesh and Rosh Ha' Ayin doubled their populations (25). This expansion increases pressure on ecosystems within and between urban areas, which include diverse habitats from Mediterranean coastal regions and mountainous forests to deserts and agricultural lands, posing unique challenges and opportunities for ecological research (e.g., 26). Further, urban infrastructure provides essential amenities and services to residents, and with most of Israel's population living in urban areas, understanding the interrelationships between humans and urban nature is crucial for sustainable development (27-29). However, **significant knowledge gaps in biodiversity patterns and dynamics hinders our ability to effectively plan, create and maintain resilient urban ecosystems that support both biodiversity and human wellbeing.**

The Importance of Urban LTERs

Long-Term Ecological Research (LTER) programs provide unique opportunities for comprehensive, long-term studies and monitoring of ecosystems, providing invaluable insights into their functioning and sustainable management (30,31). Particularly for urban environments, LTERs are critical for ensuring their sustainability, as they are at the forefront of ecological change and human-nature relationship (7). Despite being highly transformed, urban ecosystems contain all key elements of functioning ecosystems, from producers to decomposers (32). Thus, urban LTERs aim to establish a monitoring scheme addressing various ecological and anthropogenic aspects of urban ecosystems (33). Currently, and despite the global trend of rapid urbanization, only a handful of urban LTER programs operate around the world, notably in [Phoenix](#), [Minneapolis-St. Paul](#) and [Singapore](#), and until recently also in [Baltimore](#). These LTERs provide critical insights into the complex interactions between urbanization, ecological processes, and human dimensions (34). These sites examine a wide range of topics, including biodiversity, climate change, water and nutrient cycling, in conjunction with socio-ecological dynamics (35, 36). By monitoring these factors over extended periods, they also inform urban planning and policy, helping cities develop strategies that promote resilience, enhance ecosystem services, and improve the quality of life for residents (37). **Increasing the number and spatial representation of urban LTER programs around the world has the potential to foster a comprehensive understanding of urban ecology, enabling collaborative research and sharing of knowledge and best practices to address common challenges faced by urban areas worldwide.** For example, the lack of long-term monitoring of air pollution in Indian cities has led to rapid and severe reduction in ecosystem services provided by the urban vegetation, and consequently to increased levels of related human health problems (e.g., in Durgapur, West Bengal, 38). In Israel, 13 LTERs exist across the country in a diversity of habitats (<https://lter-israel.org.il/>), but none address the human-nature complex of urban areas.

An Urban LTER in Israel

Key Objectives

We propose to establish an urban LTER program that represents a significant effort towards achieving profound understanding of Israel's urban ecosystems, by focusing on two cities representing different climatic regions: Mediterranean, represented by Haifa, and hot-arid, represented by Be'er Sheva. By taking a long-term, interdisciplinary research approach, the program will provide valuable insights into the complex interactions between human activities and ecological processes in urban settings. In this LTER program we aim to pursue four key objectives regarding urban ecosystems in Israel:

1. **Establishing a baseline understanding of urban ecological systems** by characterizing biodiversity, climate, ecosystem services, and social aspects and investigating how variation in abiotic and anthropogenic urban characteristics shapes them.
2. **Exploring the relationships** between these four socio-ecological key components in urban areas to understand their mutual interactions and influences.
3. **Identifying patterns and trends over time** by analyzing spatial and temporal changes in these four components and human-nature relationship.
4. **Develop actionable policy recommendations** by translating and synthesizing scientific findings to guide urban planning and conservation efforts, aiming to enhance biodiversity, ecosystem services, and human-nature relationships in rapidly urbanizing regions like Israel.

Research Program

To pursue these objectives, we propose a LTER program comprising five interrelated work packages (WPs) that collectively provide a comprehensive understanding of urban ecosystems in Israel, culminating in urban planning policy recommendations (Figure 1). WP1-3 collectively provide the data required to address objectives 1-3. WP1 monitors urban fauna in terrestrial and aquatic habitats to assess species diversity, community composition, and population dynamics using expert and citizen (community) science methodologies. WP2 maps and monitors urban climate, vegetation, and floral fungi

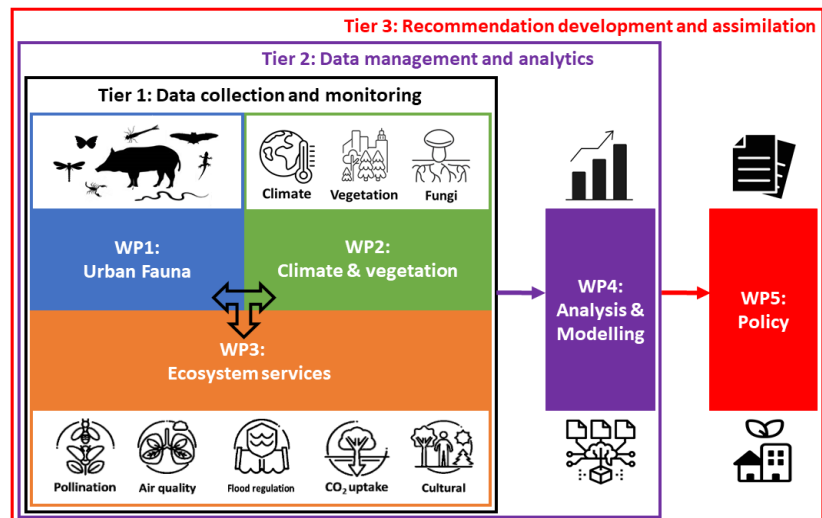


Figure 1. The proposed LTER program.

symbionts, evaluating how urbanization influences local climate and vegetation dynamics, crucial for regulating urban temperatures and supporting biodiversity and human wellbeing. WP3 assesses the contribution of urban green spaces to pollination, flood regulation, air quality, carbon sequestration, and cultural services, linking ecological health to human wellbeing and addressing objective 3 by investigating the reciprocal relationship between urban ecosystems and human activities. WP4 synthesizes data from WP1-3 using advanced analysis and modeling to explore spatio-temporal patterns and predict urban ecological scenarios, providing robust models to inform urban planning and conservation strategies, thus addressing objectives 1-3 and providing the scientific evidence for addressing objective 4. WP5 translates these research findings into policy recommendations for sustainable urban development and planning, focusing on fostering healthy human-environment interactions and promoting biodiversity through science-based policies, thus directly addressing objective 4. Collaborations between WPs will be coordinated by a board formed by representatives from all WPs, Ha'Maarag (<https://hamaarag.org.il/>), and desirably also the focal municipalities, through regular interdisciplinary meetings, shared data platforms, and integrated fieldwork activities. **This program relies on, and benefits from, the diverse expertise of its applying consortium members and employs a wide range of methods** from ecology (DM, YI, ZY, II, AL, TK), citizen science (SR, OA, YG), landscape geography (LW), climatology (DP), social sciences (MM), remote sensing (AB),

data science (SP, IS), and environmental policy (TZ), providing a synergistic perspective on urban ecosystems and generating long-term interdisciplinary infrastructure. Past research in Haifa of some members (DM, IL, AL, LW), has already generated preliminary data on various ecological aspects we propose to monitor (Appendix 1). Multiple collaborations among consortium members are ongoing (see CVs and publications lists). **Overall, the program aims to provide decision-makers with the best information for evidence-based planning in Israel's cities.**

LTER Stations

We propose to establish two urban LTER stations, in Haifa and in Be'er Sheva. In each city (i.e., LTER station), we will focus on six urban neighborhoods and one non-urban control site (Figure 2, Tables 1, 2), along with selected urban water bodies nearby the neighborhoods, encompassing all forms of urban environments: green spaces (naturally and artificially vegetated areas), gray spaces (built areas), brown spaces (abandoned areas), and blue spaces (urban freshwater bodies and their immediate vicinity). This approach captures both biotic and human diversity. We selected the suggested neighborhoods to maximize the diversity of several defining characteristics, as well as to represent a comparable set of neighborhoods between Haifa and Be'er Sheva, to the best possible extent (Table 1; counterpart neighborhood across cities share a similar # number). If required and feasible, we may expand our monitoring to 1-2 additional neighborhoods in each city over the course of the LTER, e.g., to monitor a newly built neighborhood and its developing impacts at real-time. Within each neighborhood we will sample one "grey" and one "green" site, at several plots or transects (pending on the target monitored variable), that together represent the diversity of local microhabitats, including "brown" spaces. All monitoring in WP1-3, will be conducted at the same set of sampling plots to the greatest extent possible, considering target-specific limitations and methodologies. Additionally, we will explore different social aspects of these neighborhoods' residents.

Table 1. Proposed sites (i.e., neighborhoods) and their defining characteristics. Level of open/built area ratio and socioeconomic status are relative values within each city, as both are generally higher in Haifa than in Be'er Sheva. Information sources: Israel Central Bureau of Statistics (25) and websites of the municipality of Haifa (<https://www.haifa.muni.il/>) and Be'er Sheva (<https://www.beer-sheva.muni.il/>).

City	#	Name	open/ built area ratio	Built fabric (age-density-height)	Socioeconomic status	Planned development
Haifa	1	Moshava Germanit	Low	Old-Dense-Medium	Low	None
	2	Neve David	High	Old-Sparse-Mixed	Low	Urban renewal within
	3	Neot Peres	Low	New-Dense-High	High	New construction within
	4	Ramat Begin	Medium	Mixed-Medium-Mixed	High	New construction nearby
	5	Hod Ha'Carmel	High	Mixed-Medium-Low	High	None
	6	Check-Post I.Z.	Low	Industrial-commercial Zone	Non-residential	None
	-	Mount Carmel NP	High	Non-urban	Non-urban	None
Be'er Sheva	1	Old City	Low	Old-Dense-Medium	Low	Urban Renewal nearby
	2	Gimmel	High	Old-Sparse-Mixed	Low	Urban Renewal within
	3	Ramot Ha'Reches	Low	New-Dense-High	High	New construction within
	4	Yud Alef	Medium	Mixed-Medium-Mixed	High	New construction nearby
	5	Neot Lon	High	Mixed-Medium-Low	High	New construction nearby
	6	Be'er Sheva I.Z.	Low	Industrial-commercial Zone	Non-residential	None
	-	Hatzerim Park area	Low	Non-urban	Non-urban	None

Table 2. Proposed aquatic sites (i.e., water bodies) and their geographical characteristics.

City	#	Name	type	Closest studied Neighborhood	lat	lon
Haifa	a	Ein Ahuza	Spring	Ramat Begin	32.781	34.986
	b	Ein Siach	Spring	Neve David	32.802	34.971
	c	Nahal Saadya	Stream	Check-Post I.Z.	32.789	35.026
	d	Check-Post pool	Ephemeral pool	Check-Post I.Z.	32.794	35.037
Be'er Sheva	a	Lake park	Artificial lake	Be'er Sheva I.Z.	31.237	34.825
	b	Children's park	Artificial pond	Yud Alef	31.261	34.760
	c	Nahal Be'er Sheva	Stream	Old City	31.236	34.792
	d	Neot Lon pool	Ephemeral pool	Neot Lon	31.251	34.755

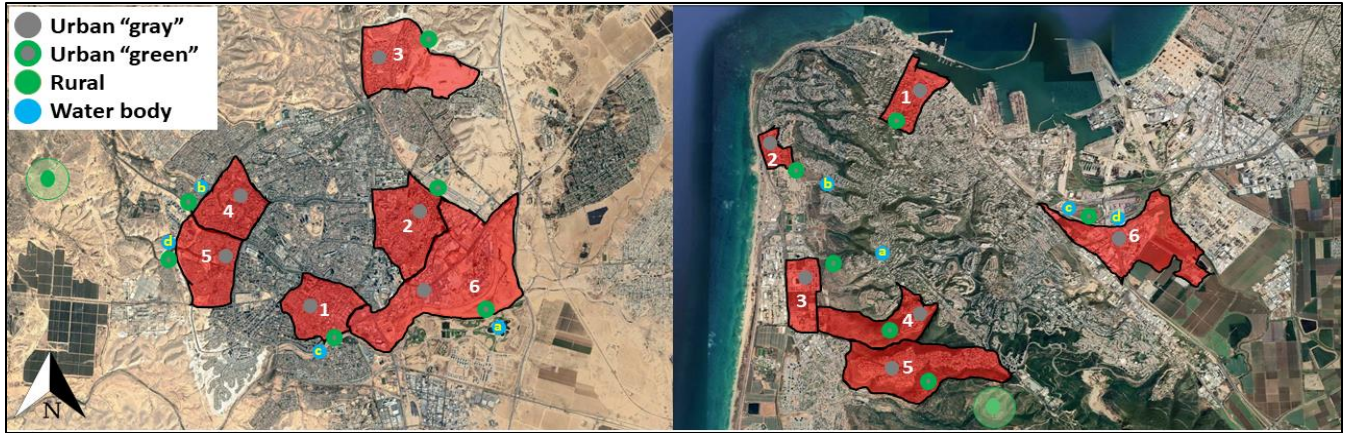


Figure 2. Suggested LTER sites: Haifa - right, and Be'er Sheva - left. Suggested neighborhoods marked in red. Numbers and letters correspond to those in Tables 1 and 2, respectively.

This design, where two cities representing different climatic zones are monitored and studied with similar methodologies, is globally unique for urban LTERs, and provides empirical infrastructure for multi-scale insights, which currently has been attempted, to a limited extent, only once – in Baltimore and Phoenix (39,40). Yet, while we plan to employ generally similar approaches, frameworks, and methodologies in both cities, some aspects of data collection, experimental designs, and research focus areas may be customized to suit the distinct characteristics of Haifa and Be'er Sheva. This customization will allow us to address region-specific questions in each city while contributing to a broader comparative framework within the proposed LTER scheme. The fundamental aim of the proposed LTER is comparing neighborhoods within each city rather than between them. However, this setup will likely yield broadscale comparisons across cities (i.e. climatic regions). Importantly, to the best of our knowledge, there is currently no other Mediterranean urban LTER, and only one urban LTER in a desert region (in Phoenix,).

Work Packages

WP1: Urban Fauna

The urban fauna, an integral component of urban ecosystems, provides critical ecosystem services and interacts with human residents in both positive and negative ways (41). Thus, effectively monitoring changes in structure and composition of the urban fauna is imperative. **We propose focusing on a variety of taxa, including aquatic invertebrates, terrestrial arthropods, reptiles, and mammals,** with particular attention to introduced species and those undergoing rapid range expansion. Long-term studies of these taxa will illuminate the dynamics of human-nature interactions in urban areas. Fear of certain species may lead to efforts to eradicate them from urban environments, an issue that we will address in our research. Habitat assessments within each focal neighborhood will evaluate physical and biological characteristics, including temperature, humidity, vegetation cover, use of natural or artificial objects and structures, and shelter availability. Comprehensively monitoring these parameters will provide insights into how urbanization impacts biodiversity and human-wildlife interactions, inform conservation strategies, and help maintain ecological balance in cities. Particularly, we will focus on exploring the following long-term patterns:

1. **Meta-community dynamics:** these illuminate population success and viability within the fragmented urban matrix, and distinguish vulnerable species from highly adapted species in the urban space. Community composition data will be used to compare habitat types and to analyze the contribution of socioeconomic features to biological findings.
2. **Biotic homogenization:** captures the long-term impacts of urbanization on biodiversity through filtering, turnover, and local extinction and colonization processes in response to environmental alterations, and identification of urban hotspots, particularly within island biogeography framework (42).
3. **Urban microclimatic effects on population dynamics:** deals with the long-term ecological impacts of climate change processes as they are expressed within urban regions.

WP 1.1 Expert Monitoring

1.1.1 Mammals

Mammals indicate ecosystem health and offer essential functions like seed dispersal and pest control (43). People often enjoy observing and feeding urban mammals, fostering positive interactions, However, negative attitudes (e.g., fear) due to potential disease transmission or property and physical damages, also prevail. Some mammals, such as (feral) domestic cats, which are an exotic element in urban ecosystems, evoke mixed reactions ranging from deep affection to loathing (44). While they help control pest rodent populations, their high densities in some areas, often due to human feeding activities, can negatively impact local species like wild rodents, birds and lizards (45). Animal feeding stations in cities can also become hubs of parasite and pathogen transmission among different wild and domestic species (46). We will focus our monitoring on medium-large mammals (e.g., herbivores, carnivores) and bats.

Methods: We will install trail cameras biannually at each monitoring site: one camera at the boundary between constructed (i.e., residential) areas and open spaces, and the other in the open space, away from constructed areas. These cameras will be deployed for two weeks each time, in the summer and winter. Videos will be automatically analyzed using an AI algorithm (47) trained to recognize specific animal types, count males, females, and cubs, and identify individual animals for species of particular interest (e.g., wild boars, jackals, cats).

We will also monitor bats, using passive bioacoustics measures (Audiomoths; 48) to gather data on activity patterns, species diversity, and responses to urbanization. Four devices will be attached to trees in different areas within each monitored neighborhood, recording bat calls for two hours after sunset and two hours before sunrise during four nights around the new moon, four times a year. We will analyze recordings using Kaleidoscope Pro Analysis Software for automatic identification of species-specific calls, including social and foraging calls.

1.1.2 Reptile and Scorpions

Reptiles and scorpions are common in urban environments, including indoors, and are essential components of urban ecosystems. Their sensitivity to environmental changes, important ecological roles, and relative ease of study make them ideal candidates for assessing the impacts of urbanization on biodiversity (49,50). As ectothermic organisms, they rely on external temperatures to regulate their body temperature, making them particularly sensitive to urban microclimatic changes. This sensitivity allows them to act as bioindicators, providing valuable insights into the health and stability of urban ecosystems and the effect of climate change and habitat fragmentation.

Reptiles play crucial roles in controlling pest populations, such as insects and rodents, maintaining ecological balance. However, they are often misunderstood and feared, leading to negative attitudes and actions. Despite this, reptiles provide significant ecological benefits and are even considered by some people to bring good luck (e.g., house geckos; 51). Scorpions, act as bioindicators of soil health and also help controlling insect pests, though their presence often raises public health concerns related to stings.

Methods: We will survey reptiles and scorpions three times a year (spring, summer, and autumn) at five sampling plots within each site using roughly similar methods for both taxa, that have proven most efficient (52,53). Visual encounter surveys will systematically search defined areas and record all individuals encountered, effective for diurnal reptiles basking in the open, nocturnal scorpions and reptiles detected using ultraviolet and regular flashlights, respectively. Rock rolling surveys will involve carefully turning over rocks and debris to find hidden reptiles and scorpions. Standardized covers (uniform-sized boards) will be placed in selected areas and checked regularly (54). Dry pitfall trapping will involve burying containers with funnels to capture ground-dwelling animals; these traps will remain open for several days and checked twice daily. Mark-recapture techniques will involve marking individuals using non-toxic paint for reptiles and fluorescent powder or small tags for scorpions to estimate spatio-temporal patterns in co-occurrence (see e.g., Appendix 1.1), population sizes, survival rates, and movement.

1.1.3 Butterflies

Butterflies, as key pollinators and reliable indicators of biodiversity and ecosystem health (55-57), support urban green spaces and engage the public in conservation efforts, enhancing human appreciation of nature through their beauty (58). However, their sensitivity to environmental changes may signal the negative impacts of urbanization.

Methods: Monitoring butterflies will be outsourced to a professional expert who will employ a combination of systematic methods to effectively assess their presence (see e.g., Appendix 1.1). Potentially, transect walks across fixed routes at regular intervals will serve to record the butterfly species and numbers encountered. Point counts, where observers stay at fixed locations for a set period, will complement the transects. Additionally, habitat assessments, including surveys of host plants and nectar sources, will help correlate butterfly presence with environmental conditions. These methods together will provide a comprehensive understanding of butterfly populations and their responses to urbanization across space and time (59).

1.1.4 Aquatic Invertebrates

Aquatic invertebrate communities are being employed for a long time as surrogates for habitat quality and resilience in freshwater systems, as their populations can be highly impacted by pollution and habitat degradation due to human activities (60). Streams, springs, ponds, and lakes are amongst the most diverse, yet vulnerable, ecosystems. Due to their unique features, some freshwater taxa have even greater meaning when present or absent. Odonates (dragonflies and damselflies) indicate water quality and habitat connectivity and contribute to pest control (61,62). Their larvae live in the water but the adults do not. They are often subject to citizen science projects, fostering a positive connection between people and aquatic environments.

Methods: Each site will be characterized through verbal descriptions and measurements of key environmental parameters (water flow, waterbody dimensions, water temperature, dissolved oxygen, pH, electric conductivity, etc.). Invertebrates will be collected using a hand-net designed for aquatic environments, with methodologies varying based on site properties (e.g., standing versus running waters; 63). These samples will be preserved in 96% ethanol and transported to the laboratory, where they will be sorted, counted, and identified to the highest possible taxonomic level by experts at the Steinhardt Museum of Natural History at Tel Aviv University. Concurrently, adult dragonfly and damselfly (Odonata) surveys will be conducted during each aquatic sampling event to complement the aquatic surveys and provide a more comprehensive invertebrate inventory.

WP 1.2 Citizen Science: Non-Expert Monitoring

Citizen science, involving non-professionals in scientific research, has become a powerful tool for biodiversity and ecological research (64). It provides substantial data, innovative methodologies, and fosters connections between scientists and the community. Citizen science projects contribute over half of the data for the Global Biodiversity Information Facility (GBIF), support 33% of the Sustainable Development Goals (SDG) indicators, and have resulted in hundreds of scientific publications (65-67). **Integrating citizen science into our proposed urban LTER enhances data collection and public engagement with environmental issues, leveraging volunteers for extensive data gathering, long-term monitoring, and increased public interest in science and nature** (68). This involvement drives behavioral changes, build community networks, and advocates for research, conservation, and policy development. This WP focuses on developing citizen science initiatives for enhancing the spatial, temporal and taxonomic cover of the biodiversity monitoring in both cities (as described in WP1.1), fostering volunteer communities that will establish a sustainable network of long-term monitoring activity beyond the grant period. We aim to create a blueprint for community building and engagement within the Israeli cultural and social context, with expertise from the Israel Center for Citizen Science (ICCS) at the Steinhardt Museum of Natural History, and following successful examples from around the world (e.g., 69,70). This will enhance recruitment and activities for our citizen science initiative, promoting it nationally. Establishing such communities will also allow exploring the impact of citizen scientists' engagement on nature connectedness and wellbeing, together with WP3.5 (see below).

Methods: We will establish citizen science communities in both cities, particularly focusing on the LTER sites (Table 1), but not exclusively. Following the ICCS's operational protocol for citizen science initiatives, we will hire a community manager at the ICCS. This manager will receive expert guidance on community engagement, citizen science, biology, taxonomy, and technological aspects. The community manager will launch and manage the communities, forming sub-groups for monitoring each taxon with specific protocols. Trained volunteers will complement professional data collection, increasing the scope of taxon monitoring and enhancing data on urban wildlife abundance and phenology. Community gatherings and workshops at the LTER stations will inform residents and train volunteers in field methods and data recording apps. All monitoring schemes will primarily rely

on two apps integrated by the ICCS: iNaturalist (<https://www.inaturalist.org>) for sporadic species observations and Bio-collect (<https://www.ala.org.au/biocollect>) for more elaborate sampling protocols. We will maintain continuous communication with volunteers, provide open access to collected data, and offer annual updates to participants. The taxon-specific sampling protocols (highly similar to expert monitoring methods in WP1.1):

- **Mammals:** Participants will record sporadic observations of mammals or their signs (e.g., footprints, feces), in parallel to expert monitoring using camera traps. Specific schemes for species of interest (e.g., wild boars in Haifa) will be implemented.
- **Reptiles:** Participants will record sporadic observations of reptiles or their signs (e.g., eggs, shed skins), as well as perform dedicated non-contact surveys for both diurnal and nocturnal species (with flashlights), in parallel to similar expert monitoring methodology, and with expert guidance (71). We will additionally record information from the Nature Protection Authority on snake removals by professional trappers.
- **Scorpions:** Participants will photograph and record individuals detected with UV torches, in parallel to expert monitoring using similar methodology.
- **Flying insects:** We will establish monitoring schemes for butterflies and odonatas, collaborating with hired experts for butterflies, and following their well-established methodologies for monitoring butterflies by citizens (72,73). The participants will document species occurrence, locations, and times.

To investigate the robustness of the data collected, we will employ statistical modeling aimed at bias correction of citizen science data through comparison with experts' data by estimating and accounting for a diversity of biases (74). The parallel data collection by experts and non-experts will contribute valuable datasets for further development of these tools, and contribute to the field of citizen science generally.

WP2: Climate and Vegetation

The urban heat island (UHI) effect, caused by the replacement of permeable, vegetated surfaces with impermeable building and paving materials that absorb and store heat, heat-trapping effects due to low effective albedo and aerodynamic drag, and heat emissions from anthropogenic sources like vehicles, heating, air-conditioning, and industrial processes (75). Traditionally, UHI intensity is measured as the maximum temperature difference between urban and rural areas. However, this "island" analogy oversimplifies the reality of urban areas, which are more accurately described as zones with varying land use, land cover, and surface temperatures. The Local Climate Zones (LCZ) approach by Stewart and Oke (76) provides a more useful framework based on site characteristics. This elevated temperature is mitigated by urban vegetation through shade and evapotranspiration, thereby regulating urban climate effects and contributing to ecological resilience. Consequently, maintaining vigorous urban vegetation is crucial. **This WP focuses on characterizing urban climate, vegetation and the fungi symbionts of trees that affect their health and functioning.**

WP 2.1 Urban Climate

Israel's location in the eastern Mediterranean basin makes it a "hot spot" that is especially sensitive to atmospheric warming trends, with a historical temperature increase of about three times the global average temperature and twice the global average Land Surface Air Temperature (77). Rising urban temperatures impact human activity and well-being through multiple interconnected pathways. Thermal stress discourages pedestrian activity and increases reliance on air-conditioned buildings and vehicles, posing health hazards to the public. The frequency, duration, and intensity of heatwaves are expected to exacerbate the surge in heat-related morbidity and mortality worldwide (78). Particularly in the semi-arid climate of Be'er Sheva and dry-subhumid (Mediterranean) climate of Haifa, thermal stress is exacerbated by exposure to intense solar radiation, which varies temporally and spatially more than any other micrometeorological parameter across the urban terrain (79). This WP is threefold: 1) tracking modifications in the local climate due to urbanization effects; 2) tracking background modifications in the regional climate due to larger-scale atmospheric effects; and 3) evaluating the impact of these trends on human thermal stress and energy consumption to promote more sustainable policy and planning responses. To pursue these aims, we will establish long-term climatic monitoring networks in Haifa and Be'er Sheva.

Methods: We will use the Local Climate Zones (LCZ) approach to select and characterize micrometeorological measurement sites in Haifa and Be'er Sheva. Additionally, we will monitor the David Tuviyahu (Beit HIAS) campus of Ben-Gurion University in Be'er Sheva, which includes diverse vegetation and shade conditions.

Monitoring systems incorporating screen-height multi-sensor units (Gil GMX501 or similar) at each site will continuously record air temperature, relative humidity, wind speed and direction, and global radiation, with reliable PV power supply, battery storage and data transmission to central servers. Data processing, analysis, and predictive modeling protocols are detailed in WP4.

Long-term monitoring in less urbanized sites, as defined by the LCZ framework, will use the same instrumentation to facilitate the identification of temperature trends relatively free of urban influences. This will help better describe changes in the regional climate and provide a reference for UHI intensity.

To address the impact of rising urban temperatures on human thermal stress and energy consumption, and potentially also animal heat stress, we will develop and implement a platform for the mapping and analysis of shade at the urban scale and its change over time. Our long-term urban climate monitoring will facilitate the predictive modeling of thermal stress in future cities and form a valuable basis for formulating responsive planning and design strategies, where shade plays an important role. Monitoring systems at each site will continuously record relevant climatic variables, ensuring comprehensive data for analysis and modeling.

WP 2.2 Urban Vegetation

Urban vegetation monitoring traditionally relies on ground-based methods, which are costly, labor-intensive, and infrequently updated. These methods also face challenges in obtaining continuous data over large areas, including private properties. Consequently, remote sensing data is increasingly used to assess urban forest parameters, estimate urban tree canopy, and detect changes in urban vegetation cover (80,81). Remote sensing allows for a digital representation of spatial features like buildings and vegetation, aiding in the analysis of interactions between open spaces and built-up areas. In this part, we will integrate advanced remote sensing and machine learning techniques to monitor urban vegetation dynamics in an efficient and accurate manner. This approach will facilitate a better understanding and management of urban forests and green spaces.

Methods: We will use orthophoto-based Red-Green-Blue imagery to compute various vegetation indices (Table S1 in Appendix 2) applying bimodal histogram thresholding to distinguish vegetation from non-vegetation and assess its status. Texture features are crucial for analyzing patterns and shapes, essential for tree species classification. To investigate the impact of color transformation techniques on classification outcomes, we will extract additional texture features by applying Gray Level Co-occurrence Matrix (GLCM) on hue, saturation and value color components (82). Detailed height information of urban trees, characterizing their vertical distribution, will be obtained using three methods: canopy and shadow classification with a Random Forest Classifier, geometric calculations based on shadow length and sun angle, and voxel conversion for detailed volume and density estimation (Figure S1 in Appendix 3). We propose the Vegetation 3D Density Index (V3DI) to quantify urban vegetation using voxels. Sample trees in diverse environments will be analyzed for crown volume with both voxels-based and traditional methods, fitting regular geometry to crown shape (83). We will measure tree height and crown diameter, and calculate the volume of coniferous and deciduous trees using cone or ellipsoid formulas, respectively, adjusted to tree parameters (84). For image segmentation, we will use the eCognition multiresolution algorithm to minimize heterogeneity within regions and facilitate precise extraction of areas with similar features. Integrating remote sensing data and Convolutional Neural Network-Long Short-Term Memory network (CNN-LSTM)-Attention techniques, we aim to improve urban vegetation analysis by extracting relevant features, reducing redundant features, compressing model training time, and enhancing prediction accuracy. The LSTM with an attention mechanism will improve prediction accuracy for spatial-temporal tree dynamics, managing long-term dependencies and selectively retaining historical information through its gate structure.

WP 2.3 Fungi Symbionts of Trees

Fungi are among the least studied organismal kingdoms, despite their crucial roles in various biological processes and geochemical cycles from micro- to global scales (85). Saprotrophic fungi are essential for nutrient cycling in both natural and human-made ecosystems (86). Symbiotic fungi, forming mycorrhiza with plant roots, are vital for plant health, aiding in seedling establishment and forming belowground networks in forests (87).

Urban ecosystems have largely been inhospitable to most fungi due to the constant removal of dead organic matter and the confined nature of urban root systems. Most urban gardens and parks are managed as engineered systems, promoting specific plant species while inhibiting almost all other organisms. However, transforming these areas

into more natural ecosystems could benefit both human and non-human communities and reduce high maintenance inputs such as pruning, fertilization, and pest management. Achieving this transformation without fungi is impossible due to their crucial roles in plant health and litter decomposition. Monitoring urban fungi can help assess whether urban gardens function as semi-natural systems or remain heavily dependent on human intervention (88).

Methods: In each plot, we will identify and document all fungal species by (i) sporocarps (fungal fruit bodies, i.e., mushrooms) and (ii) DNA identification in soil samples. For this we will extract DNA from soil, prepare a library using a PCR reaction with ITS primers, and sequence the libraries using Illumina MiSeq with 300 bp paired-end reads. Fungal species will be determined from amplicon sequence variants using advanced bioinformatic tools. We will perform soil sampling and mushroom identification five times a year: October, December, February, April, and July (once in autumn, spring, and summer, and twice in winter, which is the peak mushroom season in Israel). We will use above- and belowground fungal data to construct the seasonal fungi dynamics in each plot. We will also examine factors controlling spatial and temporal dynamics, including (i) weather conditions like temperature, rainfall, and solar radiation, (ii) micro-site conditions like plant hosts or dead organic matter, and (iii) macro-scale conditions, e.g., garden size, disturbances, pollution sources, and tree diversity (see Appendix 1.2).

WP3: Ecosystem Services: Ecological and Social Aspects

Urban ecosystems, although characterized by dense human populations, activity and infrastructure, play a crucial role in the provision of ecosystem services, i.e., the diverse benefits that humans derive from nature and human-managed ecosystems. Urban greenspaces provide a variety of highly important such services by mitigating negative urbanization effects and being highly utilized by residents and visitors. **The main goal of this WP is to evaluate the effects of greenspaces, the spatial arrangement of the urban area** (mainly the relation between green and built-up areas), **and the temporal trends across seasons and years on five ecosystem services.**

WP 3.1 Pollination

Pollinators in cities provide essential pollination and plant reproduction services in gardens, parks, allotments, and other urban green spaces (89). Cities commonly offer heterogeneous landscapes for pollinators, and especially in arid areas such as Israel, could also become refuges and corridors of favorable habitats for them (90). Thus, appropriately managed cities could enhance the conservation of pollinators and thereby act as hotspots for pollination services which are provided by wildflowers and crops grown in urban settings (91) and around it.

Methods: Pan traps will be employed to evaluate the effects of different urban green spaces and temporal trends on pollinators abundance, richness, and diversity. This is a standardized and commonly used method for collecting flying insects that is widely used in studies of pollinator communities (e.g., 92,93). Pollinators will be sampled three times per year (spring, summer and autumn) at all seven LTER sites of each city. In each plot flying insects will be sampled using blue, yellow, and white pan traps filled with unscented soapy water to be mounted on a stick at vegetation height. Pan traps will be emptied every day. Insects from traps will be stored in 95% ethanol. Insect samples from each pan will be dried, weighed, and morphologically identified. Furthermore, we will use a much more sophisticated and accurate method to identify pollinators using insect DNA barcoding (e.g., 94).

WP 3.2 Flood Regulation

As urban development increases, impervious surfaces like concrete and asphalt cover an increasing area, disrupting the natural water cycle, reducing infiltration rates, surface storage capacity and groundwater recharge while producing higher direct runoff volumes and peak flow discharges (95). In urban areas in Israel, the runoff-rainfall coefficient is estimated to be around 20%, and storm runoff can reach up to 40%, being much higher than in non-urban areas (96). Green spaces within the urban fabric increase water retention, soil infiltration and evapotranspiration, causing a significant reduction of the above ground water accumulation in the water basin and thereby mitigating downstream flood risk (97).

Methods: We will assess the contribution of green spaces and urban vegetation to flood regulation services by measuring runoff from rain events in a selected water basin in each city. Urban runoff will be measured using a hydrometric station with transmitting pressure sensors installed in an open channel downstream of the basin. This setup will capture runoff dynamics across areas with diverse land uses and building densities. Water levels will be

calibrated to create storm hydrographs and evaluate the rain-to-runoff ratio for each contributing area. Two rain gauges, one upstream and one at the outlet, will measure concentration times, storm progression, rainfall intensity, and duration. High-resolution orthophotography will map the contributing drainage basin, detailing land uses, covers, and types of green spaces and vegetation. The urban drainage system will be mapped and verified through ground surveys. Rain data will be sourced from the nearest weather station. GIS and remote sensing methods will be used to create a comprehensive database for watershed analysis and management, with data analyzed using runoff models such as SWMM (Storm Water Management Model).

WP 3.3 Air Quality

In the urban area, vegetation, especially trees, can significantly reduce the levels of air pollution through the absorption and deposition of pollutants such as soot, dust and various gaseous toxins (98). The mechanism of the service includes deposition and adsorption of particles and some gases onto leaf and branch surface, and absorption of gaseous pollutants into the plant tissues through the open stomata. In general, the size of the green space and the vegetation density are positively correlated with the reduction of air pollutants (99,100), but the extent of this effect depends on plant species, planting configuration and the wind directions and velocity, as well as the proximity to the pollution source (98). Air quality has a significant implication to human health, especially in the urban environment, in which large population is exposed to high concentrations of pollutants due to proximity to sources of pollution, such as transport and industry (101).

Despite the great knowledge that exists about the effect of trees on air quality within cities, much of it relies on models, lacking field measurements that allows to assess the spatial distribution of the services as well as trends over the years. This issue is particularly important given the climate change and the rapid development of urban areas, two phenomena that are expected to have a major effect on cities in Israel.

Methods: To assess the effect of urban green spaces on air quality and inhalable particle concentration (PM1, MP2.5, MP10) will be measured at the seven LTER sites in each city (see e.g., Appendix 1.3). In each site, two areas will be sampled, the largest contiguous greenspace in the site and the largest contiguous built-up area (buildings and/or paved surfaces) in the site. In each area a mini-meteorological station will be placed, attached to a post/light pole about 3-4 meters above the ground. To analyze seasonal and annual trends, measurement sessions (two weeks) will take place in spring, summer and winter every year. Data of all variables mentioned above (including the ones in WP 2.1) will be also collected from permanent stations of the Israel Meteorological Service (Haifa - three stations, Be'er Sheva - one station) and will be used as a reference to all other measurements.

WP 3.4 Carbon Uptake by Trees

Trees remove ~100 gigatons of CO₂ from the atmosphere annually, making them the most accessible and efficient nature-based solution to climate change. Cities are major CO₂ emitters, so planting trees in urban areas offers a direct climate change mitigation pathway (102). For example, in Canberra, Australia, planted trees were valued at US\$20–67 million over five years for their energy reduction, pollution mitigation, and carbon sequestration benefits (103). Urban tree carbon sequestration potentials have been estimated in multiple places worldwide (104-106). Despite the significant potential, efforts to maximize tree carbon uptake are hindered by inaccurate tree-scale measurements. Erroneous monitoring and reporting have affected the carbon market associated with trees. Research indicates significant differences in urban tree carbon uptake rates among species and sites (107-109).

Methods: We will employ a novel method (110,111) developed at the Weizmann Tree Lab (led by TK) to accurately and continuously measure tree carbon uptake, providing online data. Sensors installed directly on selected trees monitor carbon uptake continuously, and branch tips are sampled seasonally for carbon isotope composition to calibrate the method. This accurate, real-time measurement aims to revolutionize the use of trees to offset CO₂ emissions and mitigate climate change. Measuring trees directly allows managing city greenspaces to optimize their carbon uptake, balancing it with species diversity. This involves ensuring the selection of most suitable species and ecotypes, informed site selection, and early detection of suboptimal tree performance due to pests or competition. Tree carbon uptake will be monitored continuously in selected urban plots representing the contrasting city parts described above (e.g., a city park vs. a main street). In each research plot, we will install sensors on 10-20 trees of 2-3 tree species. Data will be transmitted directly to a web server, where our proprietary algorithms will calculate

tree carbon uptake online. Next, data will be analyzed to identify the major drivers of carbon uptake dynamics. These include key species-specific, eco-physiological, drivers like photosynthetic radiation, temperature, and humidity, as well as urban-specific factors like competition with other trees or other urban land-use patterns, all considered when estimating C uptake (see, e.g., Appendix 1.4).

WP 3.5 Cultural Services and Resident Wellbeing

Greenspaces contribute significantly to public health and well-being through environmental mitigation, recreation opportunities, and psychological restoration (112). **Extending the social aspects associated with the citizen science work (WP1.2), this WP focuses on the latter two by assessing spatiotemporal patterns of perceptions and use of urban greenspaces among local residents and the general public.** It explicitly assesses and monitors the social component of urban ecosystems, which is strongly interconnected with the changes that ecosystems undergo in urban areas. Data collection will occur in three phases, complemented by neighborhood-level environmental and socioeconomic analyses using publicly available data. Together, these methods provide a comprehensive description of neighborhood greenspace cultural services and help detect changes in seasonal and climatic cultural services within and between neighborhoods and cities.

Methods: This WP includes monitoring the social characteristics of each neighborhood (see Table S2, in Appendix 2) and collecting data on resident interaction with nature and wellbeing in three phases. All surveys will be developed according to well-accepted standards in social sciences (113).

Phase I: We will conduct an annual web-based survey among 100 adult residents (18+) in each of six neighborhoods per city, totaling 1,200 respondents, some of whom will also participate in our citizen science initiative (WP1.2). The survey, developed and pilot tested by the research team and executed by an external company to ensure a representative sample, will include questions about greenspace visitation, barriers to visitation, perceptions (accessibility, attractiveness), uses (walking, relaxing, socializing), and health outcomes (physical activity, stress relief, well-being). It will be structured into three parts: general questions, personal experiences with emotions and values, and sociodemographic variables (See Table S3 in Appendix 2). Participants will rate their emotions when visiting greenspaces with varying characteristics and observing different animals and evaluate their personal values regarding nature based on Schwartz (114). The questionnaire will also feature a choice experiment using photos of diverse urban nature landscapes, animals, and plants. The survey design will consider the inherent differences in greenspace features between cities, and participant responses will be analyzed to describe residents' perceptions and use of greenspace in general, without referring to local greenspaces, which will be assessed in Phases II and III.

Phase II: Volunteered Geographic Information (VGI) analysis of greenspaces, will be employed to assess spatiotemporal patterns of greenspace perceptions and use within and around each neighborhood. Five greenspaces per neighborhood, totaling 60 urban greenspaces, will be selected based on size, vegetation, topography, location, and VGI data availability. Social media platforms and outdoor/hiking applications (e.g., Amud Anan, Wikiloc) will be analyzed to identify popular points of interest, hiking/biking routes, and related perceptions and sentiments, complementing local residents' perspectives gathered in Phase III.

Phase III: a greenspace ranking survey will be conducted within each neighborhood, where local residents will participate in a brief web-based survey to classify the local greenspaces examined through VGI in Phase II as sites they either like or dislike and either visit or not. To cover various age groups, children, adults (18-65), and older adults (65+) will be included.

We will take advantage of this research to simultaneously explore the impact of citizen science participation on nature connectedness and well-being over time, comparing citizen scientists to the general public, as an intergraded study with the citizen science initiative. This will allow us to evaluate whether participation in environmental citizen science initiatives raises environmental awareness and promotes protective behaviors.

WP4: Analyses and Modelling

This WP focuses on maximizing the utility of the data collected and ensuring efficient data handling, comprehensive analysis, and robust predictive modeling, facilitating informed decision-making in urban planning and conservation.

WP 4.1 Data Management

We will develop a comprehensive database to integrate and store various types of data collected in the LTERs, such as biodiversity, ecosystem services, climatic, and social data (see e.g., <https://med-iter.haifa.ac.il/>). This will enable the integration of different LTER aspects for modeling and ensure standardized data management, maintaining consistency despite potential researcher turnover. We will align the data structure with standard protocols and integrate pre-existing data collected in the same areas before the LTER's establishment. It will further ensure data integrity, backup and open access, and support long-term monitoring data curation. All data generated by the citizen science initiative will simultaneously flow into an open, cloud-based database hosted by the ICCS, ensuring compatibility with other citizen science initiatives in Israel and alignment with ICCS protocols.

Building on this infrastructure, we will develop a web-based system accessible through a dedicated website for researchers, policy makers, environmental agencies, and the public. The website will offer additional resources (e.g., articles, activity information) and serve as an interface between the LTER and citizen science participants. It will feature graphical data visualization interfaces, such as maps, to make data easily understandable and engaging. The data will be openly available for download, with a flexible querying interface, to meet users' diverse needs. Additionally, we will integrate some models into the website in collaboration with the AI4biodiversity group (<https://ai4biodiversity.haifa.ac.il/architecture/>; led by DM and IS).

WP 4.2 Data Analysis

We will analyze the data at several levels. At the WP level, researchers will conduct analyses tailored to their specific research questions using pertinent methodologies (as described above), with a specific focus on spatial and temporal relationships with the monitored parameters. At the cross-WP level and the whole LTER level, we will perform integrative and interdisciplinary analyses combining various data types. For example, we will investigate how biodiversity influences public perceptions of greenspace utility, or how climatic regimes influence biodiversity and ecological services. WP4's team will lead these integrated analyses, involving the other relevant experts in the consortium. One promising framework for such analyses is Social-Ecological Networks (SEN; 115), which allows us to explore the ongoing feedback between these two complex systems and understand the ultimate consequences of their dynamics. Another promising framework is the Social-Ecological-Technical (built) System (SETS) framing, a systems approach that emphasizes the importance of technology in urban built infrastructure (116).

WP 4.3 Forecasting

This WP focuses on developing predictive models to assess how land use changes impact biodiversity, ecosystem services, and public well-being (117). These models will integrate diverse data types, including satellite images, species abundance, and ecosystem service metrics, to forecast future trajectories and understand their implications for urban planning and conservation efforts. Model components include GIS data (tree canopy cover, vegetation, water bodies, and impervious surfaces), species distribution data (presence, abundance, and distribution from field surveys, citizen science, and ecological databases), ecosystem services data (e.g., pollinator abundance, green space usage, and CO₂ uptake), and social data related to public health (e.g., mortality and morbidity related to heat stress, socio-economic variables). We will use several modeling approaches: species dynamics and distribution models (if data prove sufficient) to predict species abundance and occurrence; machine learning models like artificial neural networks to capture nonlinear relationships between data types (118), trained with spatial, temporal, ecological, and socio-economic features to generate baseline predictions and forecast land use changes; spatial simulation models (e.g., agent-based models) to simulate individual behavior in changing environments (119); and integrated assessment models (IAMs) such as Globio (<https://www.globio.info/>) and InVEST (<https://naturalcapitalproject.stanford.edu/software/invest>), which combine socioeconomic, environmental, and ecological data for integrated projections (120). We expect that this diversity of data, approaches and tools allow us to produce robust, data-driven forecasts that support effective urban planning and conservation strategies, ensuring sustainable development, improved ecosystem services, and reduced human-wildlife conflicts.

WP5: Policy

Climate change, ecological crises, population growth, and urbanization make urban natural sites crucial for the public and policymakers. Until recently, planning focused on preserving open areas for biodiversity and climate change mitigation while balancing urban needs like construction, transportation, and leisure. Now, urban natural sites are recognized as valuable, low-maintenance resources that enhance quality of life and mental health and

mitigate climate change and environmental hazards. Understanding the ecological function of urban nature and its interactions with human communities is essential for developing policies to plan, preserve, and manage urban natural areas. In the two municipalities targeted by this LTER monitoring, there is a growing understanding of urban ecology, as both cities are surrounded by nature within or adjacent to built environments. **This work package**, led by The Institute for Climate and Environmental Policy at Ben-Gurion University, **aims to supplement other work packages in establishing science-based urban ecology policy and developing comprehensive policy recommendations.**

Methods: To achieve this, the research will begin with a roundtable involving multi-sector stakeholders, including government ministries, local authorities, regional and municipal environmental units, community administrations, Nature and Parks Authority, civil society organizations, and local environmental groups, to refine needs and objectives. Surveys will be conducted among policymakers and the public in Haifa and Be'er Sheva to identify key points and focus areas. Throughout the LTER period, the research teams involved in WP1.2 and WP3.5 will accompany the process, emphasizing the interfaces between the community and policymakers through periodic consultations and updates, including via the dedicated online LTER platform we will establish (see WP4). This WP will culminate in writing policy papers with recommendations at national, local, regional, and civic levels. These recommendations and findings will be disseminated to the public and policymakers through mass media, workshops, webinars, personal meetings, community partnerships, and presentations at relevant conferences and events.

Significance of the Research

The proposed LTER program will provide seminal understandings of Israel's urban systems, addressing the rapid urbanization and the growing challenges posed by climate change, biodiversity loss, and resource scarcity. The proposed LTER will address these issues, offering a model for other regions, advancing urban ecology, and complementing existing LTER efforts in Israel. We plan to incorporate our LTER stations within Israel's LTER network. Our long-term monitoring of terrestrial and freshwater urban habitats presents unique opportunities for complementary, comparative, and integrated research across environmental realms. These continuous assessments and research are essential for planning and policy management at national, local, and civic levels, focusing on characterizing urban natural areas, integrating them into spatial planning, and managing them for conservation and public use. These efforts are critical for maintaining a sustainable and functioning urban ecosystem.

Locally, the urban LTER program's findings will provide an unprecedented baseline and long-term interdisciplinary database for two major cities in Israel and insights into mitigating the pressing environmental impacts of urbanization. This is particularly important in Israel, where urban growth intersects with water scarcity, biodiversity conservation challenges, and land use conflicts. With the majority of Israel's population residing in ever-expanding urban areas, this research will support sustainable human-nature coexistence. Globally, this research will enhance the understanding of urban ecology and sustainability. **Insights from Israel's urban ecosystems can inform practices in other regions facing similar challenges, especially in Mediterranean and arid-desert areas, thereby contributing to global urban ecology knowledge and policy.**

Expected Outcomes and Impact

The proposed LTER is expected to generate a wealth of data and insights that will inform urban planning and policy development. Key expected outcomes include:

1. **Comprehensive data sets:** Long-term data on biodiversity, ecosystem services, climate, and socio-ecological interactions in urban areas, established standardized platform for LTER data storage, and a functional and user-friendly website for data access and visualization. These datasets will be made available to researchers, policymakers, and the public to support evidence-based decision-making.
2. **Insights into long-term urban environmental patterns and processes, and best sustainability practices:** Identification of the major change drivers in urban areas, and the effective strategies and

practices for enhancing the sustainability and resilience of urban socio-ecological systems. These best practices can be integrated into urban planning and management frameworks, in different climatic regions.

3. **Enhanced public awareness, engagement, and wellbeing:** Increased awareness and engagement among urban residents regarding the importance of ecological sustainability. This will be achieved through citizen science research participation and researcher-public interaction through the citizen science interface of the dedicated LTER website, outreach programs and educational initiatives.
4. **Policy recommendations:** Development of policy recommendations aimed at promoting sustainable urban development. These recommendations will be based on rigorous scientific research and roundtable discussions with stakeholders and decision-makers, and will address key issues such as land use planning, habitat conservation, and climate adaptation.

The proposed LTER will provide the foundation for continuous monitoring, building on the establishment of the necessary physical and scientific infrastructure during the four-year funding period. This includes the continuous operation of citizen science initiatives. The interdisciplinary consortium and robust scientific infrastructure established during this period will facilitate future collaboration with other urban LTERs around the world. We aim to engage local municipalities and governmental agencies for future funding to maintain the sites. To ensure long-term viability, we estimate the need for two full-time technicians, a sustainable figure for future funding allocations given the breadth of topics studied.

Time Table and Performance Indices

The first three months will focus on preparation and site selection for WPs 1-3, initial roundtable discussions for WP5, and the first steering committee meeting. In Year 1, efforts will center on establishing monitoring sites, launching the citizen science initiative, collecting baseline data, setting up the initial database, engaging stakeholders, and distributing surveys. Year 2 will involve comprehensive seasonal data collection, establishing the citizen science communities, advanced data analysis and integration, developing initial predictive models, and drafting and refining policy recommendations, with preliminary findings prepared for publication. Year 3 will enhance data collection through community engagement, refine predictive models, conduct scenario analysis, formulate comprehensive policy recommendations, and increase stakeholder engagement and public consultations, targeting scientific publications based on refined data and models. Year 4 will complete comprehensive data collection, validate and refine predictive models, report findings, and finalize and implement policy recommendations, with a strong emphasis on publishing comprehensive research outcomes in high-impact journals. The steering committee will review the application and progress of the LTER program annually, to ensure that performance indices are met and that the project delivers the expected outcomes.

WP	Months (starting 01/2025)	Leader	0-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	
WP1	WP1.1 formal monitoring (combined)	DM, YI, ZY	site selection & preparations																
	1.1.1 mammals (via camera traps)	DM, IS																	
	1.1.2 bats	YI																	
	1.1.3 reptiles and scorpions	YI																	
	1.1.4 butterflies	(TBD)																	
	1.1.5 aquatic invertebrates	ZY																	
WP1.2 citizen science	SR, YG, OA																		
WP2	WP2.1 climate	DP	site selection & preparations																
	WP2.2 vegetation	AB																	
	WP2.3 fungi	TK																	
WP3	WP3.1 pollination	II, LW, AL	site selection & preparations																
	WP3.2 flood regulation																		
	WP3.3 air quality	TK																	
	WP3.4 CO ₂ uptake																		
	WP3.5 cultural services - phase I			MM															
	WP3.5 cultural services - phase II																		
WP3.5 cultural services - phase III																			
WP4	WP4.1 Data management	SP, IS	site selection & preparations																
	WP4.2 Data analyses	SP, DM, YI																	
	WP4.3 forecasting	SP																	
WP5	WP5: policy - stakeholder engagement	TZ	site selection & preparations																
	WP5: policy - policy papers writing																		
	WP5: policy - Public dissemination																		
General: writing scientific papers & grants																			
General: steering committee meetings																			

Figure 3. Gantt of Urban LTER of Israel. For WP1-3, the Gantt shows the data collection (i.e., monitoring) annual cycle across the first four years of the LTER. Every coloured quarter indicates at least one sampling session is planned.

References

1. Alberti, M. (2008). *Advances in urban ecology: Integrating humans and ecological processes in urban ecosystems*. Springer.
2. Li, G., Fang, C., Li, Y., Wang, Z., Sun, S., He, S., ... & Liu, X. (2022). Global impacts of future urban expansion on terrestrial vertebrate diversity. *Nature Communications*, *13*(1), 1628.
3. Pickett, S. T., Cadenasso, M. L., Grove, J. M., Nilon, C. H., Pouyat, R. V., Zipperer, W. C., & Costanza, R. (2001). Urban ecological systems: Linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. *Annual Review of Ecology and Systematics*, *32*(1), 127-157.
4. Orenstein, D. E., & Hamburg, S. P. (2009). To populate or preserve? Evolving political-demographic and environmental paradigms in Israeli land-use policy. *Land Use Policy*, *26*(4), 984-1000.
5. Keren, I., Malkinson, D., Dorman, M., Balaban, A., & Bar (Kutiel, P. (2022). The relationship between plant and butterfly richness and composition and socioecological drivers in five adjacent cities along the Mediterranean Coast of Israel. *Journal of Urban Ecology*, *8*(1), juac001.
6. Niemelä, J. (1999). Ecology and urban planning. *Biodiversity & Conservation*, *8*, 119-131.
7. Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008a). Global change and the ecology of cities. *Science*, *319*(5864), 756-760.
8. Lorenz, K., & Lal, R. (2009). Biogeochemical C and N cycles in urban soils. *Environment International*, *35*(1), 1-8.
9. Hibbs, B. J., & Sharp Jr, J. M. (2012). Hydrogeological impacts of urbanization. *Environmental & Engineering Geoscience*, *18*(1), 3-24.
10. Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083-16088.
11. Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., ... & Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, *1*(2), e1500052.
12. Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E., Cosby, B. J., Dunscomb, J. K., ... & Weathers, K. C. (2009). Effects of air pollution on ecosystems and biological diversity in the eastern United States. *Annals of the New York Academy of Sciences*, *1162*(1), 99-135.
13. Rizwan, A. M., Dennis, L. Y., & Chunho, L. I. U. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, *20*(1), 120-128.
14. Cai, Z., La Sorte, F. A., Chen, Y., & Wu, J. (2023). The surface urban heat island effect decreases bird diversity in Chinese cities. *Science of the Total Environment*, *902*, 166200.
15. Nowak, D. J. (2010). Urban biodiversity and climate change. In *Urban biodiversity and design* (pp. 101-117).
16. McKinney, M. L. (2008). Effects of urbanization on species richness: a review of plants and animals. *Urban Ecosystems*, *11*, 161-176.
17. Kowarik, I. (2011). Novel urban ecosystems, biodiversity, and conservation. *Environmental Pollution*, *159*(8-9), 1974-1983.
18. Harlan, S. L., & Ruddell, D. M. (2011). Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability*, *3*(3), 126-134.
19. Ahern, J. (2013). Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology*, *28*, 1203-1212.

20. Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P. J., McDonald, R. I., ... & Wilkinson, C. (2013). *Urbanization, biodiversity and ecosystem services: Challenges and opportunities: A global assessment*. Springer Nature.
21. Krasny, M. E., & Tidball, K. G. (2012). Civic ecology: A pathway for Earth Stewardship in cities. *Frontiers in Ecology and the Environment*, 10(5), 267-273.
22. Dennis, M., & James, P. (2016). User participation in urban green commons: Exploring the links between access, voluntarism, biodiversity and well being. *Urban Forestry & Urban Greening*, 15, 22-31.
23. Andersson, E., Barthel, S., Borgström, S., Colding, J., Elmqvist, T., Folke, C., & Gren, Å. (2014). Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services. *Ambio*, 43, 445-453.
24. The World Bank. (2022). [Urban growth data]. Accessed 24 July 2024. <https://data.worldbank.org/indicator/SP.URB.GROW?end=2022&locations=IL&start=1960&view=chart>
25. Israel Central Bureau of Statistics. (2024). [Statistical data]. Accessed 24 July 2024. <https://www.cbs.gov.il/he/Pages/default.aspx>
26. Potchter, O., & Shashua-Bar, L. (2017). Urban Greenery as a tool for city cooling: The Israeli experience in a variety of climatic zones. In *Proceedings of the PLEA, July 2017*.
27. Rofè, Y., Feierstein, G., & Zarchin, I. (2012). Quantity and quality of public open spaces in Israel. *Proceedings of the Institution of Civil Engineers-Urban Design and Planning*, 165(3), 177-187.
28. Schwartz, A., Turbé, A., Simon, L., & Julliard, R. (2014). Enhancing urban biodiversity and its influence on city-dwellers: An experiment. *Biological Conservation*, 171, 82-90.
29. Bashan, D., Colléony, A., & Schwartz, A. (2021). Urban versus rural? The effects of residential status on species identification skills and connection to nature. *People and Nature*, 3(2), 347-358.
30. Turner, M. G., Collins, S. L., Lugo, A. L., Magnuson, J. J., Rupp, T. S., & Swanson, F. J. (2003). Disturbance dynamics and ecological response: the contribution of long-term ecological research. *BioScience*, 53(1), 46-56.
31. Likens, G. E. (Ed.). (2012). *Long-term studies in ecology*. Springer-Verlag New York Incorporated.
32. Schittko, C., Onandia, G., Bernard-Verdier, M., Heger, T., Jeschke, J. M., Kowarik, I., ... & Joshi, J. (2022). Biodiversity maintains soil multifunctionality and soil organic carbon in novel urban ecosystems. *Journal of Ecology*, 110(4), 916-934.
33. Pickett, S. T., Cadenasso, M. L., & Grove, J. M. (2004). Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landscape and Urban Planning*, 69(4), 369-384.
34. Shochat, E., Lerman, S. B., Anderies, J. M., Warren, P. S., Faeth, S. H., & Nilon, C. H. (2010). Invasion, competition, and biodiversity loss in urban ecosystems. *BioScience*, 60(3), 199-208.
35. Groffman, P. M., Cavender-Bares, J., Bettez, N. D., Grove, J. M., Hall, S. J., Heffernan, J. B., ... & Steele, M. K. (2014). Ecological homogenization of urban USA. *Frontiers in Ecology and the Environment*, 12(1), 74-81.
36. Grimm, N. B., Grove, J. M., Pickett, S. T., & Redman, C. L. (2008b). Integrated approaches to long-term studies of urban ecological systems (pp. 123-141). Springer US.
37. Alberti, M. (2010). Maintaining ecological integrity and sustaining ecosystem function in urban areas. *Current Opinion in Environmental Sustainability*, 2(3), 178-184.
38. Banerjee, S., Banerjee, A., & Palit, D. (2021). Ecosystem services and impact of industrial pollution on urban health: evidence from Durgapur, West Bengal, India. *Environmental Monitoring and Assessment*, 193(11), 744.
39. Brazel, A., Selover, N., Vose, R., & Heisler, G. (2000). The tale of two climates - Baltimore and Phoenix urban LTER sites. *Climate Research*, 15(2), 123-135.

40. Roy Chowdhury, R., Larson, K., Grove, M., Polsky, C., Cook, E., Onsted, J., & Ogden, L. (2011). A multi-scalar approach to theorizing socio-ecological dynamics of urban residential landscapes. *Cities and the Environment (CATE)*, 4(1), 6.
41. Soulsbury, C. D., & White, P. C. (2015). Human–wildlife interactions in urban areas: a review of conflicts, benefits and opportunities. *Wildlife Research*, 42(7), 541-553.
42. Itescu, Y. (2019). Are island-like systems biologically similar to islands? A review of the evidence. *Ecography*, 42(7), 1298-1314.
43. Lacher Jr, T. E., Davidson, A. D., Fleming, T. H., Gómez-Ruiz, E. P., McCracken, G. F., Owen-Smith, N., ... & Vander Wall, S. B. (2019). The functional roles of mammals in ecosystems. *Journal of Mammalogy*, 100(3), 942-964.
44. Wandesforde-Smith, G., Levy, J. K., Lynn, W., Rand, J., Riley, S., Schaffner, J. E., & Wolf, P. J. (2021). Coping with human-cat interactions beyond the limits of domesticity: Moral pluralism in the management of cats and wildlife. *Frontiers in Veterinary Science*, 8, 682582.
45. Herrera, D. J., Cove, M. V., McShea, W. J., Flockhart, D. T., Decker, S., Moore, S. M., & Gallo, T. (2022). Prey selection and predation behavior of free-roaming domestic cats (*Felis catus*) in an urban ecosystem: Implications for urban cat management. *Biological Conservation*, 268, 109503.
46. Schütte, K., Springer, A., Brandes, F., Reuschel, M., Fehr, M., & Strube, C. (2024). Ectoparasites of European hedgehogs (*Erinaceus europaeus*) in Germany and their health impact. *Parasites & Vectors*, 17(1), 2.
47. Redmon, J., Divvala, S., Girshick, R., & Farhadi, A. (2016). You only look once: Unified, real-time object detection. In *Proceedings of the IEEE conference on computer vision and pattern recognition* (pp. 779-788).
48. Gibb, R., Browning, E., Glover-Kapfer, P., & Jones, K. E. (2019). Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. *Methods in Ecology and Evolution*, 10(2), 169-185.
49. Jacob, D. E., Nelson, I. U., Efenakpo, O. D., & Izah, S. C. (2024). Reptiles as Environmental Sentinels: Exploring Their Significance. In *Biomonitoring of Pollutants in the Global South* (pp. 485-533). Springer Nature Singapore.
50. Olivero, P. A., Oviedo-Diego, M. A., Vrech, D. E., Mattoni, C. I., & Peretti, A. V. (2021). Sensitivity of genital and somatic traits of scorpions to developmental instability caused by increasing urbanization: a 20-year experiment. *Ecological Indicators*, 122, 107272.
51. Frembgen, J. W. (1996). The folklore of geckos: ethnographic data from south and west Asia. *Asian Folklore Studies*, 55, 135-143.
52. Hutchens, S. J., & DePerno, C. S. (2009). Efficacy of sampling techniques for determining species richness estimates of reptiles and amphibians. *Wildlife Biology*, 15(2), 113-122.
53. Dehghani, R., Kassiri, H., & Mohammadzadeh, N. (2019). Comparison of various methods of collecting scorpions (Arachnida, Scorpiones) in Khuzestan Province, Southwestern Iran. *Archives of Clinical Infectious Diseases*, 14(4), e84452.
54. Liberman, Y. R., Ben-Ami, F., & Meiri, S. (2024). Artificial cover objects as a tool for the survey and conservation of herpetofauna. *Biodiversity and Conservation*, 33(5), 1575-1590.
55. Parmesan, C. (2003). Butterflies as bioindicators for climate change effects. In *Butterflies: Ecology and evolution taking flight* (pp. 541-560).
56. Ariyani, D., Sulistyantara, B., & Budiarti, T. (2018, August). Formulation of design concept of urban park using butterflies as a good urban environment bio-indicator. In *IOP Conference Series: Earth and Environmental Science* (Vol. 179, No. 1, p. 012024). IOP Publishing.

57. Pallottini, M., Goretti, E., Argenti, C., La Porta, G., Tositti, L., Dinelli, E., ... & Cappelletti, D. (2023). Butterflies as bioindicators of metal contamination. *Environmental Science and Pollution Research*, 30(42), 95606-95620.
58. Lim, V. C., Sing, K. W., Chong, K. Y., Jaturas, N., Dong, H., Lee, P. S., ... & Wilson, J. J. (2022). Familiarity with, perceptions of and attitudes toward butterflies of urban park users in megacities across East and Southeast Asia. *Royal Society Open Science*, 9(11), 220161.
59. Tiple, A. D., Deshmukh, V. P., & Dennis, R. L. (2005). Factors influencing nectar plant resource visits by butterflies on a university campus: implications for conservation. *Nota lepidopterologica*, 28(3/4), 213.
60. Bonada, N., Prat, N., Resh, V. H., & Statzner, B. (2006). Developments in aquatic insect biomonitoring: a comparative analysis. *Annual Review of Entomology*, 51, 495-523.
61. Smith, J., Samways, M. J., & Taylor, S. (2007). Assessing riparian quality using two complementary sets of bioindicators. *Biodiversity and Conservation*, 16, 2695-2713.
62. Miguel, T. B., Oliveira-Junior, J. M. B., Ligeiro, R., & Juen, L. (2017). Odonata (Insecta) as a tool for the biomonitoring of environmental quality. *Ecological Indicators*, 81, 555-566.
63. Hughes, J. (Ed.). (2018). *Freshwater ecology and conservation: Approaches and techniques*. Oxford University Press.
64. Bedessem, B., & Ruphy, S. (2019). Scientific autonomy and the unpredictability of scientific inquiry: The unexpected might not be where you would expect. *Studies in History and Philosophy of Science Part A*, 73, 1-7.
65. Chandler, M., See, L., Copas, K., Bonde, A. M., López, B. C., Danielsen, F., ... & Turak, E. (2017). Contribution of citizen science towards international biodiversity monitoring. *Biological Conservation*, 213, 280-294.
66. Fraisl, D., Campbell, J., See, L., Wehn, U., Wardlaw, J., Gold, M., ... & Fritz, S. (2020). Mapping citizen science contributions to the UN sustainable development goals. *Sustainability Science*, 15, 1735-1751.
67. Chaubey, A. K., & Singh, A. (2021). Analysis of citizen science scientific publications: A scientometric study. *Library Philosophy and Practice*, 1-13.
68. Putman, B. J., Williams, R., Li, E., & Pauly, G. B. (2021). The power of community science to quantify ecological interactions in cities. *Scientific Reports*, 11(1), 3069.
69. Skarlatidou, A., Hamilton, A., Vitos, M., & Haklay, M. (2019). What do volunteers want from citizen science technologies? A systematic literature review and best practice guidelines. *JCOM: Journal of Science Communication*, 18(1).
70. Anderson, A. A., Williams, E., Long, M., Carter, E., & Volckens, J. (2020). Organizationally based citizen science: Considerations for implementation. *Journal of Science Communication*, 19(3), A01.
71. Barrows, C. W., Hoines, J., Vamstad, M. S., Murphy-Mariscal, M., Lalumiere, K., & Heintz, J. (2016). Using citizen scientists to assess climate change shifts in desert reptile communities. *Biological Conservation*, 195, 82-88.
72. Valente-Neto, F., Roque, F. O., Rodriguez, M. E., Juen, L., & Swan, C. M. (2016). Toward a practical use of Neotropical odonates as bioindicators: testing congruence across taxonomic resolution and life stages. *Ecological Indicators*, 61, 952-959.
73. Comay, O., Ben Yehuda, O., Benyamini, D., Schwartz-Tzachor, R., Pe'er, I., Melochna, T., & Pe'er, G. (2020). Analysis of monitoring data where butterflies fly year-round. *Ecological Applications*, 30(8), e02196.
74. Arazy, O., & Malkinson, D. (2021). A framework of observer-based biases in citizen science biodiversity monitoring: Semi-structuring unstructured biodiversity monitoring protocols. *Frontiers in Ecology and Evolution*, 9, 693602.
75. Oke, T. (1982). The energetic basis of urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108, 1-24.

76. Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, 93(12), 1879–1900.
77. Furshpan, A., & Yosef, Y. (2021). Is Israel warming up? Israel Meteorological Service (<https://ims.gov.il/en/node/1431>).
78. Lüthi, S., Fairless, C., Fischer, E. M., Scovronick, N., Armstrong, B., Coelho, M. D. S. Z. S., ... & Vicedo-Cabrera, A. M. (2023). Rapid increase in the risk of heat-related mortality. *Nature Communications*, 14(1), 4894.
79. Aleksandrowicz, A., & Pearlmutter, D. (2022). The significance of shade provision in reducing street-level summer heat stress in a hot Mediterranean climate. *Landscape and Urban Planning*, 229(3), 104588.
80. García, M., Saatchi, S., Ustin, S., & Balzter, H. (2018). Modelling forest canopy height by integrating airborne LiDAR samples with satellite radar and multispectral imagery. *International Journal of Applied Earth Observation and Geoinformation*, 66, 159-173.
81. Laforteza, R., & Giannico, V. (2019). Combining high-resolution images and LiDAR data to model ecosystem services perception in compact urban systems. *Ecological Indicators*, 96, 87-98.
82. Ben-Shoushan, R., & Brook, A. (2023). Fused thermal and RGB imagery for robust detection and classification of dynamic objects in mixed datasets via pre-trained high-level CNN. *Remote Sensing*, 15(3), 723.
83. Korhonen, L., Vauhkonen, J., Virolainen, A., Hovi, A., & Korpela, I. (2013). Estimation of tree crown volume from airborne lidar data using computational geometry. *International Journal of Remote Sensing*, 34(20), 7236-7248.
84. Estornell, J., Velázquez-Martí, B., Fernández-Sarría, A., & Martí, J. (2018). Lidar methods for measurement of trees in urban forests. *Journal of Applied Remote Sensing*, 12(4), 046009-046009.
85. Blackwell, M. (2011). The Fungi: 1, 2, 3... 5.1 million species?. *American Journal of Botany*, 98(3), 426-438.
86. Osono, T. (2007). Ecology of ligninolytic fungi associated with leaf litter decomposition. *Ecological Research*, 22, 955-974.
87. Smith, S. E., & Read, D. J. (2010). *Mycorrhizal symbiosis*. Academic Press.
88. Newbound, M., Mccarthy, M. A., & Lebel, T. (2010). Fungi and the urban environment: A review. *Landscape and Urban Planning*, 96(3), 138-145.
89. Geslin, B., Le Féon, V., Folschweiller, M., Flacher, F., Carmignac, D., Motard, E., ... & Dajoz, I. (2016). The proportion of impervious surfaces at the landscape scale structures wild bee assemblages in a densely populated region. *Ecology and Evolution*, 6(18), 6599-6615.
90. Hall, D. M., et al. (2017). The city as a refuge for insect pollinators. *Conservation Biology*, 31(1), 24-29.
91. Theodorou, P., Radzevičiūtė, R., Lentendu, G., et al. (2020). Urban areas as hotspots for bees and pollination but not a panacea for all insects. *Nature Communications*, 11, 576.
92. Westphal, C., et al. (2008). Measuring bee diversity in different European habitats and biogeographical regions. *Ecological Monographs*, 78, 653–671.
93. Tremblay, L., & Underwood, E. (2023). *Guidelines for monitoring pollinators in urban habitats, 2023*. EU Horizon 2020 Safeguard Project, Grant agreement No 101003476.
94. Suganthi, M., Abirami, G., et al. (2023). A method for DNA extraction and molecular identification of aphids. *MethodsX*, 10, 102100.
95. Oswald, C. J., Kelleher, C., Ledford, S. H., Hopkins, K. G., Sytsma, A., Tetzlaff, D., ... & Voter, C. (2023). Integrating urban water fluxes and moving beyond impervious surface cover: A review. *Journal of Hydrology*, 618, 129188.

96. Mozes, T. A., Earl, A., Brenner, A., Deltic, A., Wallach, R., & Friedler, E. (2014). From nuisance to resource - management and restoration of urban runoff water in a water sensitive city. *Land: A Journal of the Institute for Land Policy Research*. KKL – JNF.
97. Nedkov, S., & Burkhard, B. (2012). Flood regulating ecosystem services—Mapping supply and demand, in the Etropole municipality, Bulgaria. *Ecological Indicators*, *21*, 67-79.
98. Janhäll, S. (2015). Review on urban vegetation and particle air pollution—Deposition and dispersion. *Atmospheric Environment*, *105*, 130-137.
99. Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, *4*(3-4), 115-123.
100. Lotan, A., Grosbard, S., Safriel, U., & Feitelson, E. (Eds.). (2019). *Israel National Ecosystem Assessment, Key Findings Report*. Hamaarag - Israel's National Nature Assessment Program. The Steinhardt Museum of Natural History. Tel-Aviv University. (in Hebrew).
101. Potchter, O., Shashua-Bar, L., Boltanski, D., Cohen, P. & Yaakov, Y. (2009). *The effect of vegetation and built-up elements on the microclimate conditions, air quality and noise in urban open spaces – measurements in situ, simulations and guidelines for sustainable planning*. Final report of research 802-6 for the Ministry of Environmental Protection. (in Hebrew).
102. Jo, H. K. (2002). Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *Journal of Environmental Management*, *64*(2), 115-126.
103. Brack, C. L. (2002). Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution*, *116*, S195-S200.
104. Nowak, D. J., & Crane, D. E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution*, *116*(3), 381-389.
105. Agbelade, A. D., & Onyekwelu, J. C. (2020). Tree species diversity, volume yield, biomass and carbon sequestration in urban forests in two Nigerian cities. *Urban Ecosystems*, *23*(5), 957-970.
106. Havu, M., Kulmala, L., Kolari, P., Vesala, T., Riikonen, A., & Järvi, L. (2022). Carbon sequestration potential of street tree plantings in Helsinki. *Biogeosciences*, *19*(8), 2121-2143.
107. Velasco, E., Roth, M., Norford, L., & Molina, L. T. (2016). Does urban vegetation enhance carbon sequestration? *Landscape and Urban Planning*, *148*, 99-107.
108. Weissert, L. F., Salmond, J. A., & Schwendenmann, L. (2017). Photosynthetic CO₂ uptake and carbon sequestration potential of deciduous and evergreen tree species in an urban environment. *Urban Ecosystems*, *20*, 663-674.
109. Trlica, A., Hutyra, L. R., Morreale, L. L., Smith, I. A., & Reinmann, A. B. (2020). Current and future biomass carbon uptake in Boston's urban forest. *Science of the Total Environment*, *709*, 136196.
110. Klein, T., & Hoch, G. (2015). Tree carbon allocation dynamics determined using a carbon mass balance approach. *New Phytologist*, *205*(1), 147-159.
111. Klein, T., Rotenberg, E., Tatarinov, F., & Yakir, D. (2016). Association between sap flow-derived and eddy covariance-derived measurements of forest canopy CO₂ uptake. *New Phytologist*, *209*(1), 436-446.
112. Hartig, T., Mitchell, R., De Vries, S., & Frumkin, H. (2014). Nature and health. *Annual Review of Public Health*, *35*(1), 207-228.
113. De Vaus, D., & de Vaus, D. (2013). *Surveys in social research*. Routledge.
114. Schwartz, S. (2012). An overview of the Schwartz Theory of Basic Values. *Online Readings in Psychology and Culture*, *2*(1), 1-20.
115. McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., ... & Qureshi, S. (2016). Advancing urban ecology toward a science of cities. *BioScience*, *66*(3), 198–212.
116. Grimm, N. B., Cook, E. M., Hale, R. L., & Iwaniec, D. M. (2016). A broader framing of ecosystem services in cities: Benefits and challenges of built, natural, or hybrid system function. In Seto,

- K. C., Solecki, W., & Griffith, C. A. (Eds.), *The Routledge handbook of urbanization and global environmental change* (pp. 203-212). Routledge.
117. Carrus, G., Dadvand, P., & Sanesi, G. (2017). The role and value of urban forests and green infrastructure in promoting human health and wellbeing. In Pearlmutter, D., et al. (Eds.), *The urban forest*. Future City, vol 7. Springer, Cham.
118. Filippi-Mazzola, E., & Wit, E. C. (2024). Modeling non-linear effects with neural networks in relational event models. *Social Networks*, 79, 25-33.
119. Filatova, T., Verburg, P. H., Parker, D. C., & Stannard, C. A. (2013). Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environmental Modelling & Software*, 45, 1-7.
120. Veerkamp, C. J., Loreti, M., Benavidez, R., Jackson, B., & Schipper, A. M. (2023). Comparing three spatial modeling tools for assessing urban ecosystem services. *Ecosystem Services*, 59, 101500.

List of Appendices:

Appendix 1 – Preliminary Results

Appendix 2 – Supplementary Tables

Appendix 3 – Supplementary Figures

Appendix 1 – Preliminary Results

1.1 Urban Fauna in Haifa

As part of a study titled "The contribution of Haifa green skeleton to ecological quality and the well-being of the city's residents" conducted in the past three years, an ecological survey was carried out in the spring of 2022, as collaborative work of AL, DM, LW, and II from our applying consortium. The survey covered 104 polygons across nine different neighborhoods in the city, including two neighborhoods that are part of the proposed program, Neve David and Ramat Begin. In this survey, butterflies, reptiles, birds, and small mammals were sampled using standard methods with some adaptations to the urban environment. The survey recorded nearly 7,300 birds from 57 species, 541 butterflies from 13 species, and 186 reptiles from 10 species. Additionally, footprints of seven species of small mammals were identified in approximately two-thirds of the 312 footprint tunnels placed throughout the city. In sum, this study revealed significant differences in species richness and the number of individuals between neighborhoods (Figure P1) and among the types of green spaces in the city of Haifa (Figure P2).

For example, differences in species richness and the number of individuals can be seen when comparing Neve David and Ramat Begin neighborhoods in their butterfly survey results (Table P1). From one hand there are similarities in the total number of species and the mean number per polygon in urban nature, natural areas just outside the residential space. From the other hand, in the green spaces within the built area, the number of species and the number of observed butterflies per polygon were always higher in Ramat Begin as well as the total number of butterfly individuals in the neighborhood.

The most common species in both neighborhoods, as well as in the other surveyed neighborhoods in Haifa, was the Large White (*Pieris brassicae*). Another common species, the Aegean Meadow Brown (*Maniola telmessia*), was very common only to Ramat Begin where it was observed at every site compare to Neve David where it was observed only in one urban nature site. These differences between the two neighborhoods can be related to their location – while Ramat Begin is surrounded by large natural areas and close to the Carmel National Park, Neve David is surrounded mostly by other built areas.

Table P1. Numbers of butterfly species and individuals that were observed in Neve David and Ramat Begin neighborhoods in Haifa ecological survey, spring 2022.

	Neve David		Ramat Begin	
	Species	Individuals	Species	Individuals
Urban nature (mean per polygon)	4	13	3.67	66.67
Urban green spaces within built area (mean per polygon)	0.9	1.2	1.55	6.36
Total numbers	8	38	7	171

In addition, in all taxonomic groups, wild species and human commensal species, including invasive ones, were observed. For example, 95% of all the birds observed belong to 15 species. Among the six most common species (which make up about 70% of the recorded individuals), five are defined as human companion species, with the most common being the Common myna (*Acridotheres tristis*), a well-known aggressive invasive species. Furthermore, species that are typical to natural Mediterranean scrubland that can adapt to human environments, such as the Great tit (*Parus major*), white-spectacled bulbul (*Pycnonotus xanthopygos*), and various Warbler (*Sylvia*) species, were observed in large numbers. The Common swift (*Apus apus*), a migratory species that nests in building walls, was also observed frequently.

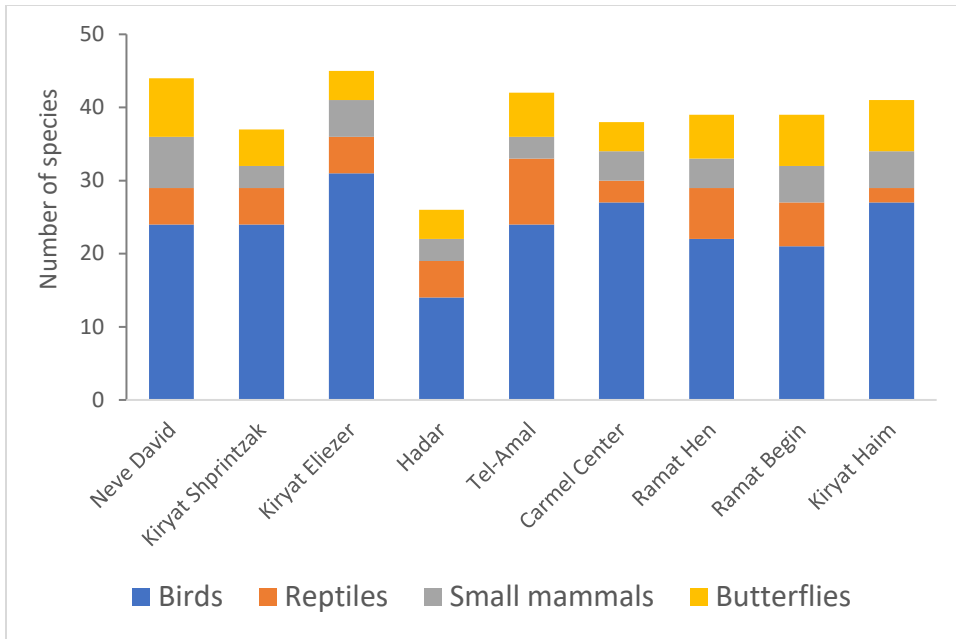


Figure P1. Cumulative number of species of the surveyed animal taxa. Results show the values for all nine surveyed neighborhoods in Haifa.

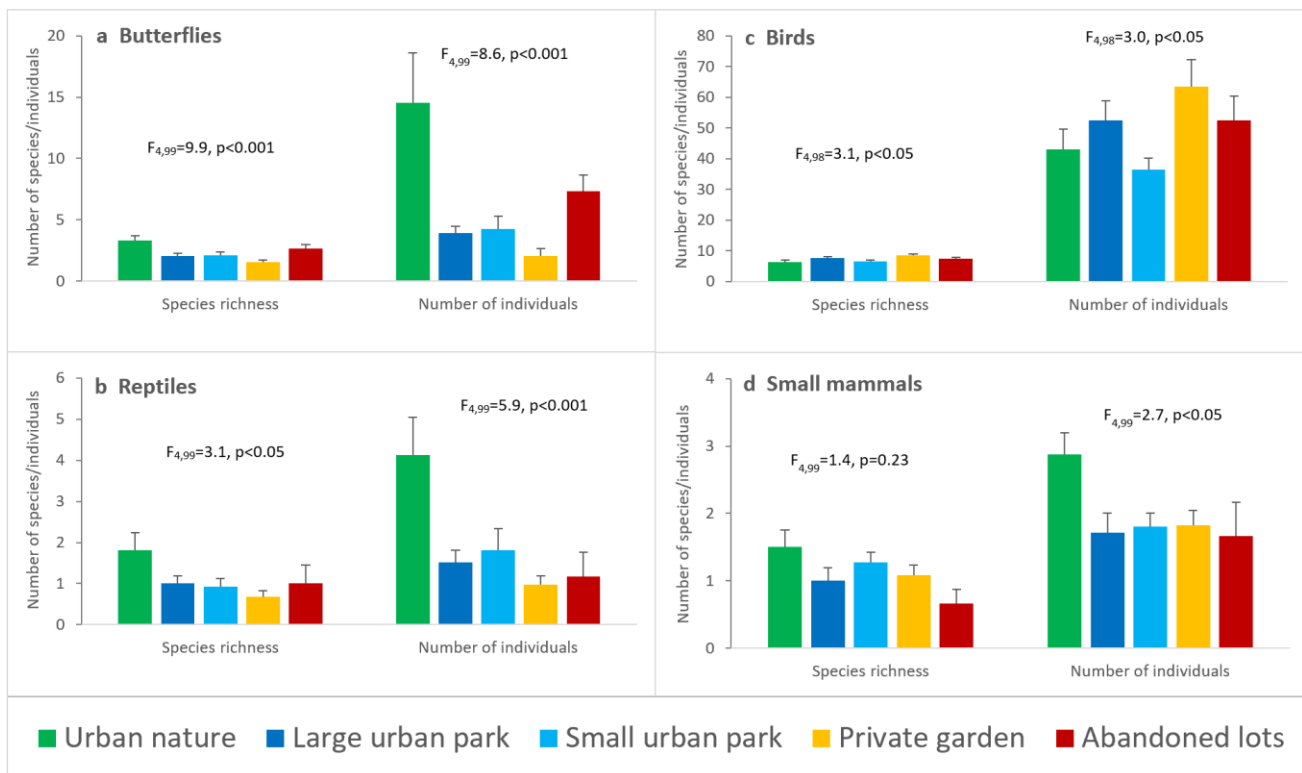


Figure P2. Species richness and number of individuals (mean + standard error per polygon) that were observed in different types of green spaces in Haifa. Butterflies (a); Reptiles (b); Birds (c); and Small mammals (d).

Patterns of reptile distribution and co-occurrence (Figure P3) showed that in Neve David reptiles were absent from most of the sampled plot, while in Ramat Begin most plots hosted at least one species. They further showed spatial patterns of distribution between mountain neighborhoods (e.g. Ramat Begin) and lower-city neighborhoods (e.g., Neve David)

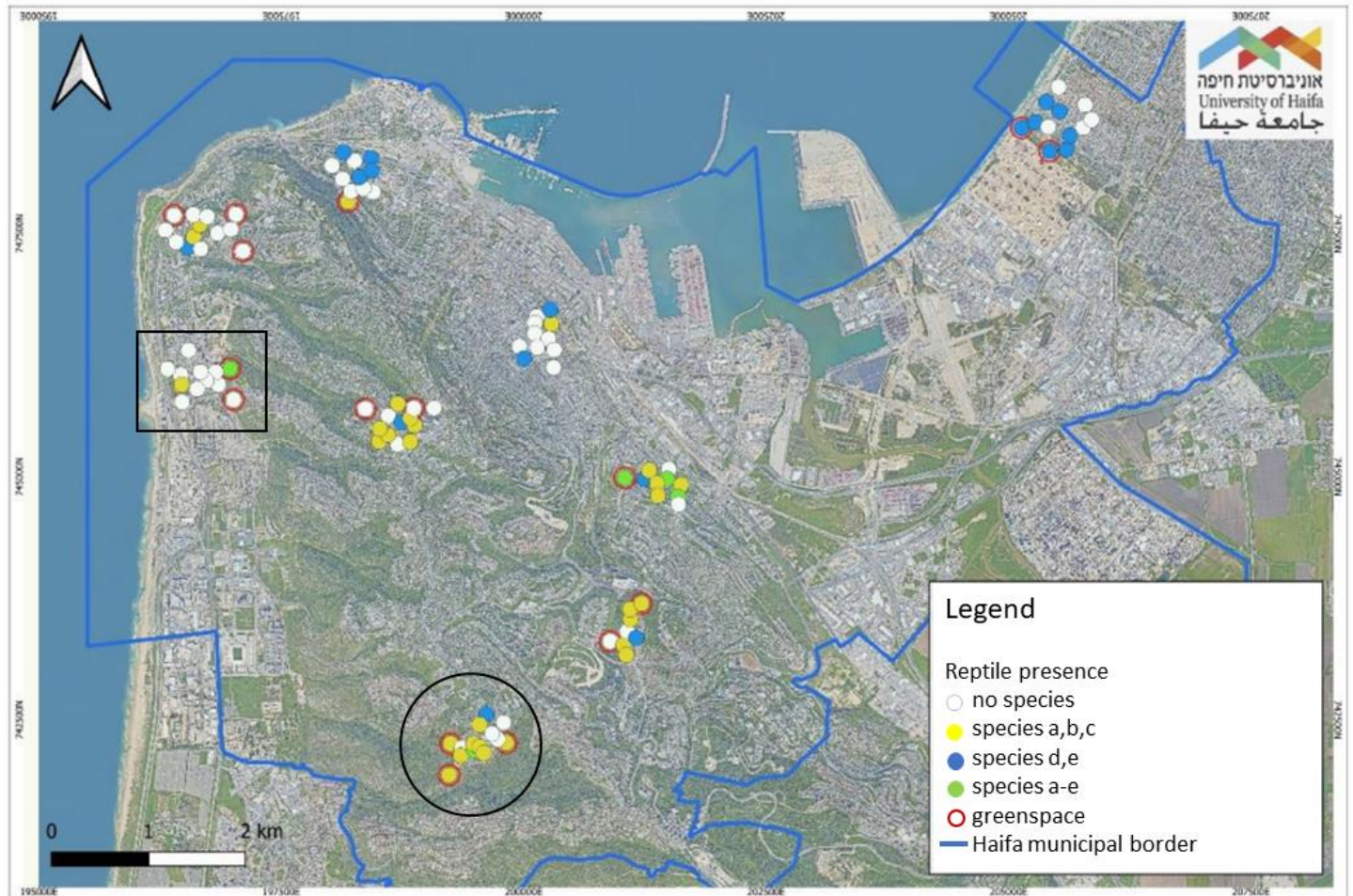


Figure P3. Co-occurrence of common lizard species across selected neighborhoods of Haifa. Species featured in this map are: *Phoenicolacerta laevis* (a); *Heremites vittatus* (b); *Mediodactylus orientalis* (c); *Chalcides ocellatus* (d); and *Hemidactylus turcicus* (e). Neve David is squared and Ramat Begin is circled. Colored circles in the legend indicate that at least one of the listed species was found in the plot.

1.2 Fungi Symbionts of Trees

Studying fungal diversity (abundance) on roots of the major forest tree species in Israel (Aleppo pine, cypress, common oak, carob, and pistacia), TK and his team found 28 abundant fungal species, with overlap among species (Figure P4a). When growing these tree species together in a confined container, only 5 abundant fungal species were identified, on all tree species (Figure P4b). When growing these tree species in separate pots, only 11 fungal species were identified, with very little overlap among tree species (Figure P4c). These results suggest that fungal diversity is very sensitive to soil volume and tree host diversity. We therefore hypothesize that in urban ecosystems, fungal diversity will increase with garden size and the diversity of plants in the garden.

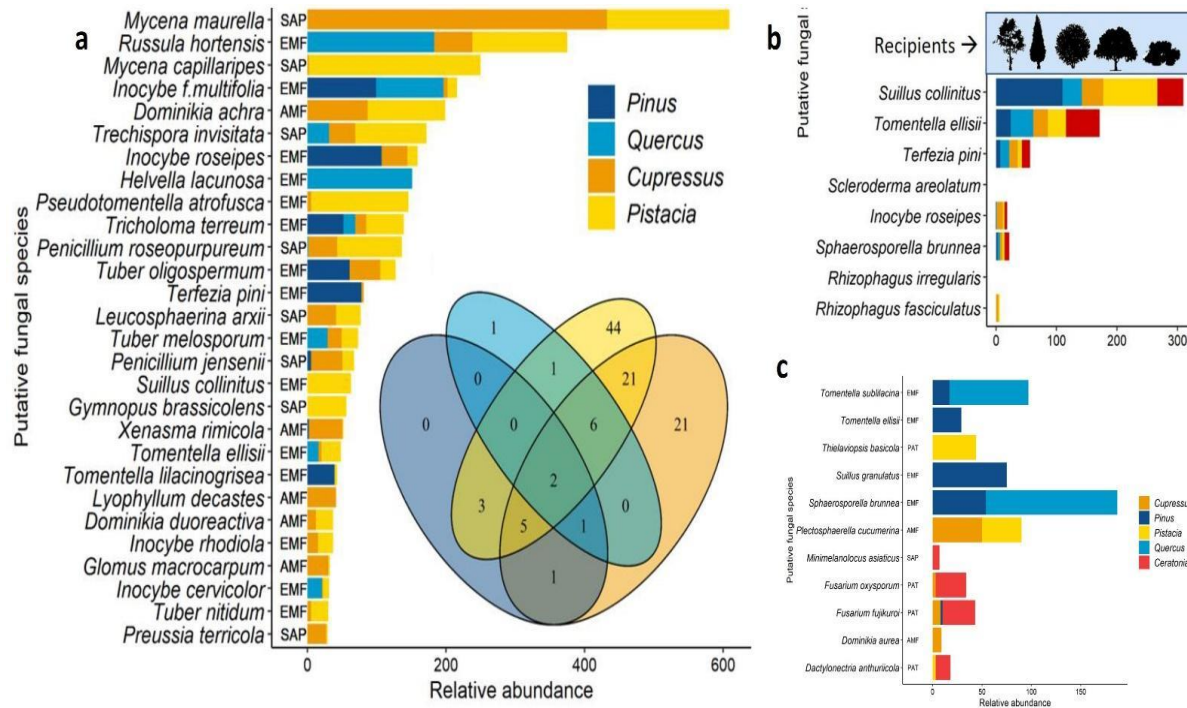


Figure P4. Fungal and host diversity is reduced with soil volume. Bars represent tree hosts (colors; 5 tree species in total) of the relative abundance of specific fungal species in a ~100 m forest plot (a); in a ~1 m container (b), and in individual, ~0.1 m pots. Venn diagram shows the overlap in fungal species among tree species (carob is missing from the forest plot analysis).

1.3 Air quality regulation

In order to evaluate the effect of the green/open spaces in the city of Haifa on the local climate and air quality, the concentrations of inhalable particle matters (PM_1 , $PM_{2.5}$, PM_{10}) were measured the nine neighborhoods where the ecological survey took place (See Appendix 1.1 above). In each neighborhood, two areas were marked, the largest/contiguous green area in the neighborhood and the largest/contiguous built-up area (buildings and/or paved surfaces) in the neighborhood. In each area, a mini-meteorological station, including PM measurement device, was placed for about 11 days in November 2023 at a height of about 3-4 meters above the ground.

The preliminary results from Neve David and Ramat Begin for $PM_{2.5}$ (the PM fragment which is often used as an indicator for air quality) show different pattern in each neighborhood. While at Neve David the daily maximum value was always higher in the green space in comparison to the built area (Figure P5a), at Ramat Begin it was the opposite in 8 out of 11 days (Figure P5b). The results also show some similarities between different days of measurements, e.g., at November 13, 14 and 19 $PM_{2.5}$ concentrations were higher than the other days. Considering the distance between these two neighborhoods these results indicate for the effect of larger spatial scale.

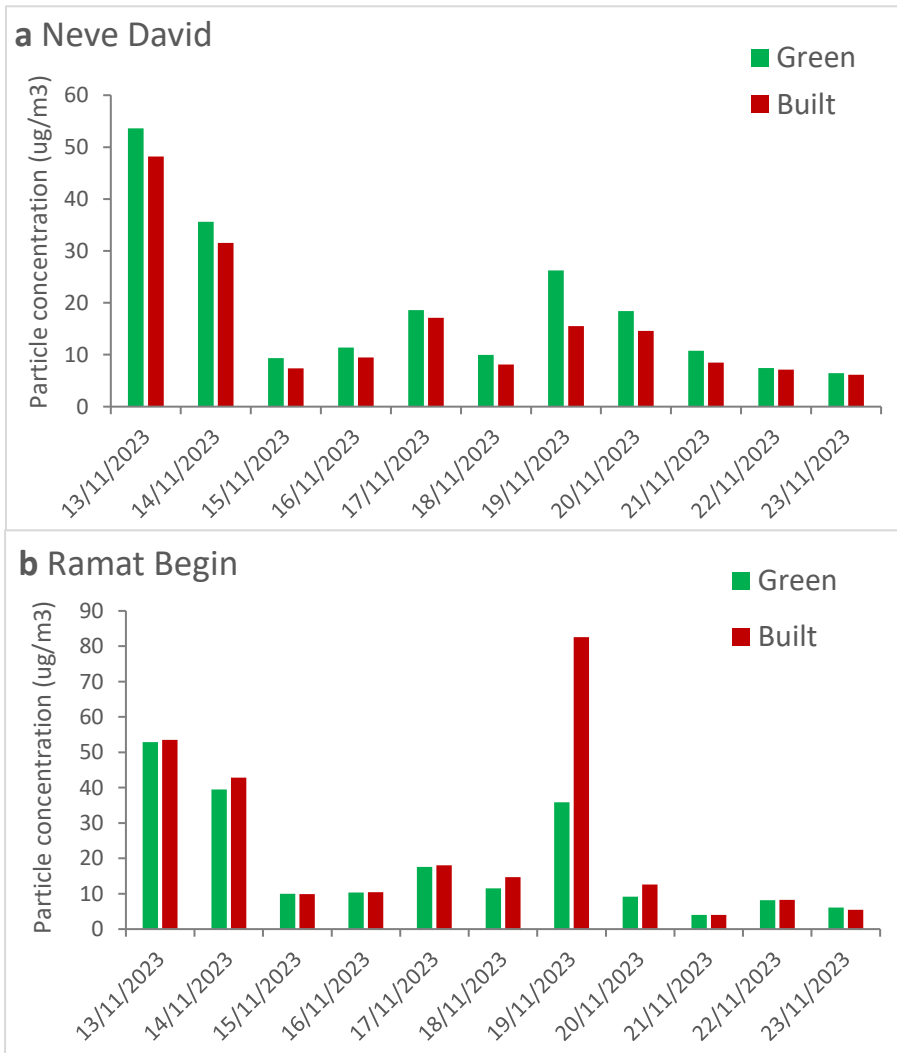


Figure P5. Daily maximum of $PM_{2.5}$ (based on hourly means) at green and built areas in selected neighborhoods of Haifa, November 2023. Neve David (a) and Ramat Begin (b).

1.4 Carbon uptake by trees

In the past ten months, TK and his team have been conducting a proof-of-concept application on 100 selected trees at the Weizmann campus gardens, a large city park (125 ha) within the city of Rehovot, Israel. We analyzed the distributions of >6500 trees according to species and sizes and installed sensors on 100 representative trees from 12 tree species (Figure 1.4.1). These trees represent the most common tree species in city parks in Israel, i.e., Mediterranean conifer species like cypress and pine; tropical broadleaf species like Ficus and Jacaranda; and common urban fruit trees like Citrus, Olive, and Mango. We have been continuously monitoring tree carbon uptake in these trees since August 2023, bringing wealth of knowledge and new information (Figure P6). Specifically, we can show now how much carbon (in g tree⁻¹ day⁻¹) do trees of each species uptake concurrently and during the past days; which species and individuals outperform others, and which lag behind; and calculate the total tree carbon uptake of the entire campus gardens. For example, we identified species-specific seasonal behaviors, like high carbon uptake by Mediterranean species like olive in fall (*Olea*; Figure P7) and cypress in winter (*Cupressus*). We can also see the effect of leaf shedding in spring in tropical species like *Jacaranda* and *Dalbergia*.



Figure P6. Tree carbon uptake monitoring examples. (a) sensor installation on a tree stem; (b) application on a mango tree in an orchard context; (c) application on a eucalypt tree in a city park context.

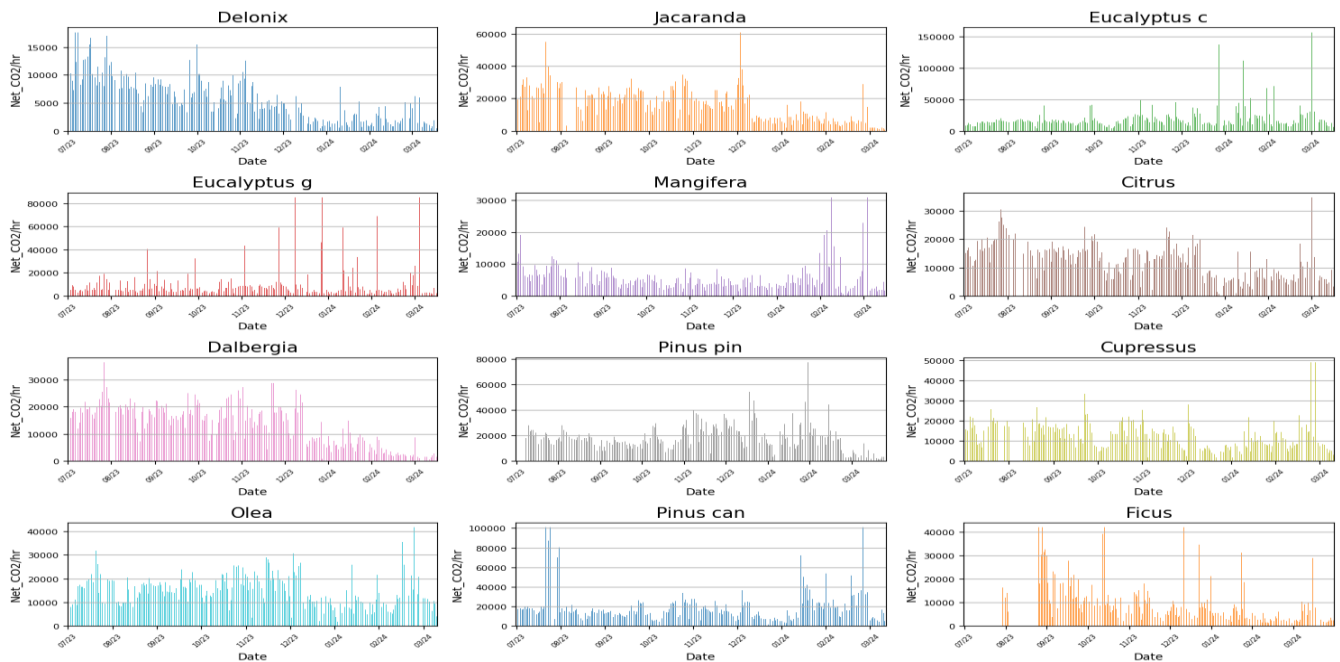


Figure P7. Tree carbon uptake rates (g tree⁻¹ day⁻¹). Results are for the period of July 2023 to April 2024 in 12 tree species (6-10 individual trees per species) growing on the Weizmann Institute of Science campus.

Appendix 2 – Supplementary Tables

Table S1. Vegetation indices to be estimated using orthophoto-based RGB imagery. In the formulas, R=red, G=green, B=Blue.

	Acronym	Full name	Formula	Reference
1	DEVI	Difference Enhanced Vegetation Index	$G/3G+R/3G+B/3G$	Zhou et al., 2021
2	EGRBDI	Excess Green-Red-Blue Difference Index	$((2G)^2-B*R)/((2G)^2+B*R)$	Gao et al., 2020
3	RGBVI	Red-Green-Blue Vegetation Index	$(G^2-B*R)/(G^2+B*R)$	Bendig et al., 2015
4	VARI	Visible Atmospherically Resistant Index	$(G-R)/(G+R-B)$	Gitelson et al., 2002
5	EXG	Excess Green Index	$2G-R$	Woebbecke et al., 1995

References (order corresponds to Table S1)

- Zhou, J., Chen, J., Chen, X., Zhu, X., Qiu, Y., Song, H., ... & Cui, X. (2021). Sensitivity of six typical spatiotemporal fusion methods to different influential factors: A comparative study for a normalized difference vegetation index time series reconstruction. *Remote Sensing of Environment*, 252, 112130.
- Gao, Y., Lin, Y., Wen, X., Jian, W., & Gong, Y. (2020). Vegetation information recognition in visible band based on UAV images. *Transactions of the Chinese Society of Agricultural Engineering*, 36(3), 178-189.
- Bendig, J., Yu, K., Aasen, H., Bolten, A., Bennertz, S., Broscheit, J., ... & Bareth, G. (2015). Combining UAV-based plant height from crop surface models, visible, and near infrared vegetation indices for biomass monitoring in barley. *International Journal of Applied Earth Observation and Geoinformation*, 39, 79-87.
- Gitelson, A. A., Kaufman, Y. J., Stark, R., & Rundquist, D. (2002). Novel algorithms for remote estimation of vegetation fraction. *Remote sensing of Environment*, 80(1), 76-87.
- Woebbecke, D. M., Meyer, G. E., Von Bargen, K., & Mortensen, D. A. (1995). Color indices for weed identification under various soil, residue, and lighting conditions. *Transactions of the American Society of Agricultural Engineers*, 38(1), 259-269.

Table S2. Neighborhood characteristics to be monitored. Neighborhood data will be evaluated for exogenous statistical administrative units (AGAS).

	Construct	Variables	Data source
Neighborhood environmental characteristics	Density indices	Population density (people per area)	City GIS data
		Residential density (household per area)	City GIS data
		Built coverage (% built up area per total area)	City GIS data
		Land uses (e.g., % retail area)	City GIS data
	Greenspace indices	Greenness (NDVI)	Satellite imagery (Landsat)
		Urban parks	City GIS data
		Trees canopy	Survey of Israel (MAPI)
Neighborhood social characteristics	Socioeconomic indicators	Neighborhood level education	Israeli central bureau of statistics
		Neighborhood level average income	Israeli central bureau of statistics
	Safety and security indices	Crime reports	Israel's police
		Traffic accident reports	Ministry of Transport and Road Safety

Table S3. Variables to be monitored in the social surveys of WP3.5 – phase I.

Part	Sections	Construct/survey module	Variables/survey questions
1. General questions	Health outcomes	General health	Self-rated health
			Quality of life
		Physical health	Chronic health conditions
			Chronic health illness
			Immune system
		Mental health	Stress
			Depression
			Anxiety
		Social health	Social networks
			Social support
			Social capital
		Park use	Park use and related behaviors
Physical activity			
Sedentary behavior			
2. Personal experiences with emotions and values	Greenspace perceptions	Greenspace perceptions and attitudes	Perceived access to greenspaces
			Nature affinity
			Nature experience
			Nature preferences – choice experiment
	Wildlife Perceptions	Wildlife perceptions and attitudes	Perceived frequency of urban wildlife observations
			Urban wildlife emotional impacts
			Nature conservation values
			Wildlife preferences – choice experiment
3. Socio-demographics	Background variables	Demographics characteristics	age, sex, ethnicity etc.
		Socioeconomic characteristics	income, education etc.

Appendix 3. Supplementary Figures

Figure S1. Surface 3d scaling model. A flowchart of the modeling process and its components.

