UNIVERSIDAD DE GRANADA

Programa de Doctorado en Biología Fundamental y de Sistemas

Tesis Doctoral

LA INFRAESTRUCTURA VERDE URBANA EN CIUDADES MEDITERRÁNEAS: CARACTERIZACIÓN Y EVALUACIÓN DE SU CAPACIDAD EN LA MITIGACIÓN DE OLAS DE CALOR

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Granada, Abril 2024

Editor: Universidad de Granada. Tesis Doctorales
Autor: Manuel José Delgado Capel
ISBN: 978-84-1195-414-3
URI: https://hdl.handle.net/10481/94693

Financiación

Este trabajo de investigación contó con el apoyo financiero parcial para la publicación de dos de los tres artículos requeridos para presentar esta tesis en formato de agrupación de publicaciones. La financiación fue proporcionada por:

- Grupo de investigación del Plan Andaluz de Investigación e Innovación (PAIDI) RNM-170 Flora, Vegetación y Etnobotánica.
- Proyectos de Investigación Precompetitivos, Plan Propio de la Universidad de Granada, a través del proyecto PP2022.PP.34, Pre-GREENMITIGATION3.
- Grant C-EXP-167-UGR23, financiado por la Consejería de Universidad, Investigación e Innovación y por el Programa FEDER de Andalucía 2021–2027.

Indicios de calidad de las publicaciones

Título	Towards a Standard Framework to Identify Green Infrastructure Key Elements in Dense Mediterranean Cities
Autores	Manuel Delgado-Capel, mdelgado@correo.ugr.es; Paloma Cariñanos, palomacg@ugr.es
Revista / Vol./ Nº/ Págs.	Forests 2020, 11(12), 1246
DOI	https://doi.org/10.3390/f11121246
INDICIOS DE CALIDAD	
FACTOR DE IMPACTO (2020)*	IF: 2.635; JCR. Categoría: FORESTRY; JCR Ranking: Q1 (13/67)
Nº Citas	17

* Último del que se tienen datos en JCR.

Título	Capacity of Urban Green Infrastructure spaces to ameliorate heat wave impacts in Mediterranean compact cities: Case study of Granada (South-eastern Spain).
Autores	Manuel Delgado-Capel, mdelgado@correo.ugr.es; Paloma Cariñanos, palomacg@ugr.es; Marcos Escudero-Viñolo, marcos.escudero@uam.es
Revista / Vol./ Nº/ Págs.	Land 2023, 12(5), 1076
DOI	https://doi.org/10.3390/land12051076
INDICIOS DE CALIDAD	
FACTOR DE IMPACTO (2020)*	IF: 3.9; JCR. Categoría: ENVIRONMENTAL SCIENCES; JCR Ranking: Q2 (48/128)
Nº Citas	2

* Último del que se tienen datos en JCR.

Título	Assessing the Relationship between Land Surface Temperature and Composition Elements of Urban Green Spaces during Heat Waves Episodes in Mediterranean Cities.
Autores	Manuel Delgado-Capel, mdelgado@correo.ugr.es; Paloma Egea-Cariñanos, palomaegeac@ugr.es; Paloma Cariñanos, palomacg@ugr.es
Revista / Vol./ Nº/ Págs.	Forests 2024, 15(3), 463
DOI	https://doi.org/10.3390/f15030463
INDICIOS DE CALIDAD	
FACTOR DE IMPACTO (2022)*	IF: 2.9; JCR. Categoría: FORESTRY; JCR Ranking: Q1 (17/69)
Nº Citas	

* Último del que se tienen datos en JCR.

Agradecimientos

La semilla de este trabajo viene de mi abuelo. Y de mi abuela. Se gestó en Suecia. Se hizo verbo en el CSIC. Cogió forma en SIVE, y maduró en Málaga. Cuatro hogares, tres oficios, dos empresas, un álbum y mucha gente que me quiere alrededor. Las cosas a dedicación parcial requieren una fuerza compleja y consistente.

Y todo mi agradecimiento,

A Paloma, por dirigirme en esta aventura tan vocacional como apasionante. Aprender es crecer. Gracias. A Paloma y Marcos, gracias por ser cruciales en las publicaciones. A Martín, Bellido, GSD, y resto de compañeras y compañeros de trabajo. Su tiempo, entendimiento y espacio han sido vitales para cerrar este capítulo. A Basilio y Begoña, por su altruismo. A mi querida peña, por darme aire los martes. A *Inundo*, gracias siempre por preguntarme y escucharme con interés. A mis 4 magníficos amigos, que me apoyan incondicionalmente desde hace 25 años ya. A la comunidad, que me ha venido dando tazas de cariño, siempre. A CDG, mi zona de confort para echar el freno cuando hace falta, y por leer. Christian, gracias por acelerar cuando ha sido necesario. A Paco, por darme serenidad en la ciencia. Daniel, Cerrillo, gracias por ver crecer este proyecto desde arriba. A mi familia, por darme apoyo desde los Cármenes de la Muralla hasta donde se apaga el Guadalquivir. A mis queridos primos, por acompañarme, al salir y al entrar. A mi padre, por remar desde la distancia. A mi tita, por guiarme al pensar. A mi *Persea americana*, esto es gran parte tuyo. A mis hermanas, la consistencia en gran parte es gracias a vosotras. Y a mi madre, luz, pilar y ejemplo de mi vida.

ÍNDICE

RESUMEN

Contexto y objetivos.

Sostenibilidad y mitigación del cambio climático son dos de los grandes retos planteados a las ciudades desarrolladas actuales. Replantear paradigmas existentes en la planificación urbanística orientándolos a mejorar las condiciones de habitabilidad y salubridad para la ciudadanía, resulta prioritario, especialmente en un contexto donde el cambio climático intensifica a nivel global la ocurrencia de episodios meteorológicos extremos y de gran impacto en entornos urbanos. En este sentido, la región mediterránea se perfila como una de las más vulnerables frente a este tipo de eventos en las próximas décadas. La presente tesis doctoral se contextualiza especialmente en las crecientes temperaturas globales y el aumento en la frecuencia e intensidad de las olas de calor, que se han convertido en foco destacado de la investigación sobre el cambio climático en ámbitos urbanos. En este contexto, la infraestructura verde urbana (UGI, por sus siglas en inglés, *Urban Green Infraestructure*) se presenta como una solución basada en la naturaleza que contribuye directamente a la mitigación del cambio climático en ciudades compactas y mejora las condiciones ambientales, sociales, de salud y de bienestar de los habitantes. Por un lado, este estudio aborda la caracterización de los elementos verdes públicos urbanos y periurbanos que pueden formar parte de la UGI a nivel local. Por otro lado, se evalúa el servicio ecosistémico de regulación que proporcionan las áreas de la UGI, específicamente en la regulación de la temperatura urbana durante periodos de máximo estrés térmico, tales como las olas de calor. En consecuencia, los objetivos planteados se centran en identificar y clasificar los elementos de la UGI mediante un protocolo escalable y transferible, analizar qué tipo de zonas amortiguan mejor los impactos de las olas de calor y, entre las áreas que mejor mitigan el estrés térmico durante estos episodios extremos, determinar qué elementos de composición superficial y qué tipos de áreas, en función de sus componentes, reducen la probabilidad de alcanzar mayores valores de temperatura superficial del suelo (LST), entendida como un indicador ajustado del estrés térmico.

Desarrollo.

Para llevar a cabo los objetivos planteados se estableció un protocolo para la identificación de la UGI en una ciudad mediterránea compacta (Granada, Sureste de la Península Ibérica). Se creó un esquema operativo, secuencial y práctico para definir, localizar y categorizar áreas públicas verdes urbanas y periurbanas, en base a en criterios de distribución espacial, extensión y capacidad de aprovisionamiento de servicios ecosistémicos. El escenario resultante ofreció una mayor superficie verde funcional, en el que las áreas identificadas se categorizaron como núcleos, nodos, enlaces y zonas verdes de menor tamaño definidas como "Other", también conocidas como SPUGS (por sus siglas en inglés, *Smaller Public Urban Green Spaces*). Con objeto de identificar aquellos tipos de área dentro de la UGI con mayor potencial de amortiguar los

impactos derivados de las olas de calor en entornos urbanos, se analizó la correlación existente entre la temperatura superficial del suelo (LST) y el índice de vegetación de diferencia normalizada (NDVI), asociando una correlación más negativa a una mayor capacidad de amortiguar el estrés térmico. Ambos parámetros, LST y NDVI, se obtuvieron a partir de imágenes satelitales OLI/TIRS correspondientes a los satélites Landsat 8 y 9, en las fechas correspondientes a los episodios de olas de calor registrados desde 2017 a 2023 en la ciudad de Granada. Tras determinar qué tipo de áreas dentro de la UGI presentaron una mayor capacidad de refrigeración en la matriz urbana (identificadas como SPUGS), se procedió a examinar la asociación, dirección y fuerza de determinadas variables en el poder explicativo alcanzar ciertos rangos de LST en cada evento de ola de calor. Para ello, se realizaron regresiones ordinales con el fin de analizar el efecto de los componentes superficiales de las SPUGS (árboles, arbustos, cobertura herbácea y distintos tipos de pavimentos), orientación y tipología de SPUGS (como variables independientes) en los rangos de LST alcanzados (como variables dependientes).

Conclusiones.

Los resultados de esta tesis doctoral ofrecen un valioso aporte al conocimiento sobre la infraestructura verde urbana (UGI), específicamente en el contexto de las ciudades compactas de la región mediterránea. El protocolo propuesto de identificación de la UGI cubre la demanda de herramientas sencillas y efectivas para el reconocimiento y categorización de la superficie efectiva de este tipo de infraestructura. La UGI definida revela el papel significativo de los pequeños espacios verdes públicos (SPUGS) a nivel estructural y ecológico en la matriz urbana. Los resultados subrayan la capacidad de las SPUGS para amortiguar los impactos de las olas de calor, mostrando una fuerte correlación negativa entre la LST y el NDVI durante estos eventos extremos. En cuanto a los componentes específicos, los árboles han demostrado ser fundamentales para disminuir la probabilidad de alcanzar rangos de LST más elevados, mientras que pavimentos empedrados de alto albedo también muestran potencial para disminuir esta probabilidad. Sin embargo, ciertos tipos de cobertura vegetal, como superficies ocupadas por especies herbáceas y césped, pueden aumentar la probabilidad de alcanzar rangos de LST más elevados en condiciones de mayor estrés térmico. Entre los tipos de áreas, las plazas tradicionales y parques, caracterizados por sus pavimentos de empedrado, acompañados de árboles y pequeñas áreas dispersas de jardín arbustivo (áreas TSQ), los parques pequeños y jardines, y las áreas peatonales con árboles y pavimentos principalmente impermeables, mostraron un mayor capacidad de reducir la probabilidad de exceder valores de LST por encima de 41 °C, en comparación con zonas verdes públicas principalmente ocupadas por vegetación herbácea o césped y con presencia de árboles y arbustos dispersos. En todos los episodios de olas de calor considerados, las áreas TSQ evidenciaron asociaciones estadísticamente más fuertes y significativas, mostrando coeficientes negativos que indicarían una mayor eficacia para reducir la probabilidad de alcanzar valores elevados de LST y, en consecuencia, amortiguar de forma más efectiva el estrés térmico. Este estudio subraya la necesidad de continuar la investigación en este campo, incorporando otras disciplinas relacionadas con aspectos biológicos, la calidad del aire y la circulación atmosférica, así como con especialidades relacionadas con la arquitectura, el diseño y la ingeniería de materiales. En particular, se delimita de forma ajustada un marco de trabajo para próximos análisis más específicos sobre la composición, selección y uso de especies vegetales que puedan proporcionar una base sólida para el diseño de espacios verdes más resilientes en entornos urbanos de la región mediterránea. Como conclusión general, la presente tesis doctoral resalta el valor agregado que las SPUGS pueden ofrecer. Principalmente, estas áreas destacan por su papel crucial en la provisión de servicios ecosistémicos de regulación, como es la gestión de la temperatura urbana y la mejora del confort térmico. Este estudio no solo consolida el conocimiento existente, sino que también proporciona perspectivas valiosas para avanzar en la gestión sostenible de los entornos urbanos, destacando la importancia de la UGI como una herramienta efectiva para abordar los desafíos asociados al contexto climático actual y futuro.

CAPÍTULO 1. INTRODUCCIÓN GENERAL Y OBJETIVOS

1. Introducción.

Los entornos urbanos actuales encuentran en la mitigación y adaptación al cambio climático uno de los principales retos para avanzar en la mejora de la sostenibilidad, habitabilidad y resiliencia de las ciudades. Según Naciones Unidas, se estima que el 55% de la población mundial vive actualmente en áreas urbanas, una proporción que se espera aumente al 68% para el año 2050 (United Nations Department of Economic and Social Affairs, 2019). Este incremento plantea el desafío de reevaluar y transformar ciertos paradigmas existentes en la planificación urbanística, orientándolos a mejorar las condiciones de habitabilidad y salubridad para la ciudadanía, especialmente en un contexto donde el cambio climático intensifica a nivel global la ocurrencia de eventos climáticos extremos (Clarke et al., 2022; Hughes et al., 2018). Entre estos fenómenos meteorológicos adversos se incluyen las olas de calor, las inundaciones, las sequías o los episodios de frío extremo, entre otros eventos climáticos de intensidad significativa (World Meteorological Organization, 2022). La presente tesis doctoral se contextualiza en las crecientes temperaturas globales y el aumento en la frecuencia e intensidad de las olas de calor, que se han convertido en foco destacado de la investigación sobre el cambio climático en ámbitos urbanos, principalmente por sus implicaciones significativas en la salud, la energía y el medio ambiente (Breshears et al., 2021; Marx et al., 2021; Santamouris, 2020).

El año 2023 ha sido confirmado oficialmente por diversas series de datos internacionales como el año más cálido históricamente registrado hasta enero de 2024, lo que subraya la urgencia de desarrollar estrategias eficaces que permitan a las ciudades mitigar y adaptarse a los impactos asociados a este calentamiento progresivo ("Data.GISS: GISS Surface Temperature Analysis (GISTEMP v4)," n.d., "World Meteorological organization," n.d.). En particular, las olas de calor en áreas urbanas de todo el mundo han experimentado un aumento significativo en su recurrencia y magnitud desde la década de 1980 (Almazroui et al., 2021; Dosio Alessandro; Mentaschi Lorenzo; Fischer Erich Markus; Wyser Klaus, 2018). Es preciso puntualizar que una ola de calor se define, comúnmente, como un período prolongado de tiempo inusualmente caluroso que dura varios días y noches de forma consecutiva, y que se caracteriza y se declara de forma objetiva mediante índices basados en condiciones climatológicas locales ("Homepage | World Meteorological Organization WMO," n.d.). El Sexto Informe de Evaluación del Panel Intergubernamental sobre Cambio Climático (IPCC) subrayó en el año 2022 la evidencia robusta del aumento de días cálidos y temperaturas extremas a nivel global, con un énfasis particular en las olas de calor en el sur del Mediterráneo (IPCC, 2022). En esta línea, los datos presentados ese mismo año por el Servicio de Cambio Climático de Copernicus destacaron el impacto crítico de estos episodios de temperaturas extremas en toda la región europea, que sufrió el verano más caluroso registrado hasta la fecha, siendo los países del Mediterráneo occidental (la Península Ibérica y zonas de Francia e Italia) los más afectados ("Global Climate Highlights 2022

| Copernicus," n.d.). En suma, la región mediterránea se perfila como una de las más vulnerables a episodios climáticos extremos en las próximas décadas, anticipando un incremento de temperatura de 2.2°C para 2040 y una posible intensificación de hasta un 20% en eventos extremos (tales como sequías o precipitaciones intensas) en todas las estaciones del año, excepto en verano. ("MedECC: Risks associated to climate and environmental changes in the Mediterranean region," n.d.). En concreto, para la Península Ibérica, se anticipa un incremento significativo en la frecuencia y duración de las olas de calor en el medio plazo (2046-2065), con un aumento estimado entre 2 y 4 veces, y un incremento alarmante entre 4 y 40 veces más en el largo plazo (2081-2100) (Lorenzo et al., 2021; Pereira et al., 2017). Esta tendencia creciente de las olas de calor bajo condiciones climáticas futuras, también observada en términos de extensión espacial, conlleva una mayor exposición humana, además de otros efectos asociados como impactos ecológicos, riesgos naturales y energéticos que precisan de soluciones efectivas y sostenibles de cara al futuro inmediato (Palipane and Grotjahn, 2018; Schoetter et al., 2015).

En este sentido, la gestión de la infraestructura verde urbana (UGI, por sus siglas en inglés, *Urban Green Infraestructure*) se presenta como una solución basada en la naturaleza (NBS, por sus siglas en inglés, *Nature Based Solution)* adecuada para adaptar los entornos urbanos a los efectos del cambio climático, contrarrestar la densificación en las ciudades, mejorar la provisión de espacios verdes públicos, disminuir la degradación ambiental así como contribuir a la reducción de la inequidad social (Escobedo et al., 2019; European Commission, 2015; Gill et al., 2007; Maes et al., 2019). La Comisión Europea proporciona una definición completa y coherente de infraestructura verde, y la describe como "*una red de zonas naturales y seminaturales y de otros elementos ambientales, planificada de forma estratégica, diseñada y gestionada para la prestación de una extensa gama de servicios ecosistémicos. Incorpora espacios verdes … y otros elementos físicos de espacios terrestres … y está presente en los entornos rurales y urbanos*" ("EUR-Lex - 52013DC0249 - EN - EUR-Lex," n.d.). Como exponente tipo, los bosques urbanos y periurbanos han destacado por ofrecer una amplia gama de servicios ecosistémicos, incluyendo aquellos de aprovisionamiento, regulación y culturales, aunque el carácter versátil, idóneo y eficaz de toda la UGI en su conjunto como solución basada en la naturaleza para las ciudades, radica en su capacidad para aumentar este extenso abanico de beneficios a lo largo de otras superficies funcionales del entorno urbano. Estos beneficios abarcan desde la regulación del clima local, la mejora de la calidad del aire y de las condiciones de salud hasta la promoción de la cohesión social o el aumento de la percepción de bienestar, entre otros (Baró and Gómez-Baggethun, 2017; Dadvand and Nieuwenhuijsen, 2018; Demuzere et al., 2014; Dobbs et al., 2018; Engemann et al., 2019; Enssle and Kabisch, 2020; Hong et al., 2019; Millennium Ecosystem Assessment Program, 2005).

La integración de la infraestructura verde urbana en marcos estratégicos a diferentes escalas es esencial para comprender cómo las políticas y directrices vigentes consideran la UGI en la planificación y gestión de los entornos urbanos. Para dar contexto general y desde una perspectiva amplia, resulta necesario conocer los enfoques de las principales normativas, estrategias e iniciativas a nivel internacional, comunitario y nacional que deberían servir como punto de partida para la incorporación y gestión de la infraestructura verde en las ciudades. A nivel internacional, cabe destacar que el Programa de las Naciones Unidas para el Medio Ambiente señala en su informe sobre infraestructuras basadas en la naturaleza que la incorporación de las NBS a la infraestructura urbana puede llegar a tener una influencia directa en el 95% de los objetivos de desarrollo sostenible (de los 17 marcados) de la Agenda 2030 (United Nations Environment Programme, 2023), subrayando así su papel fundamental para promover el desarrollo sostenible en las ciudades, aunque sin especificar instrumentos concretos y prácticos de implementación. En el ámbito comunitario, la Estrategia de Infraestructura Verde de la Unión Europea ("EUR-Lex - 52013DC0249 - EN - EUR-Lex," n.d.), adolece de cierta falta de continuidad y actualización, contando con una versión original en 2013 y un documento de revisión en 2019, mostrando directrices y conceptos muy genéricos. Además, aunque la estrategia reconoce la importancia de las soluciones de infraestructura verde en entornos urbanos, ofrece escasa orientación específica sobre cómo implementarlas. Otro marco de trabajo relevante a nivel europeo es la Estrategia de Biodiversidad de la Comisión Europea para 2030 ("Biodiversity strategy for 2030 - European Commission," n.d.), aunque hasta el momento las secciones centradas en la naturaleza y la biodiversidad solo hacen referencia al documento de 2013 sobre la anteriormente mencionada Estrategia de Infraestructura Verde de la UE. Por último, a nivel comunitario, se destacan iniciativas como el Acuerdo Verde Urbano (*Green City Accord*) y los Planes de Naturaleza Urbana (*Urban Nature Plans)* ("Green City Accord - European Commission," n.d., "Urban Nature Platform - European Commission," n.d.), que apuntan de forma genérica a conservar y mejorar la biodiversidad urbana y promover la creación de nuevas áreas verdes, conectando con algunas oportunidades de financiación, aunque aún carecen de herramientas específicas para la identificación de espacios verdes públicos urbanos susceptibles de formar parte de una UGI. Por último, en España, el marco de referencia es la Estrategia Nacional de Infraestructura Verde y de Conectividad y Restauración Ecológica ("BOE-A-2021-11614 Orden PCM/735/2021, de 9 de julio, por la que se aprueba la Estrategia Nacional de Infraestructura Verde y de la Conectividad y Restauración Ecológicas.," n.d.), vigente desde julio de 2021. Esta estrategia hace referencia a una guía metodológica que si bien "*proporciona criterios normalizados para la identificación de elementos y componentes territoriales a incorporar a la Infraestructura Verde … la metodología específica para la identificación de la infraestructura verde urbana se abordará en futuras actualizaciones*" (MITECO, 2020), por lo que el alcance concreto de la UGI no se cubriría de manera adecuada en los términos necesarios. En el contexto nacional, es necesario destacar la "Guía de la Infraestructura Verde Municipal" como un documento esencial que ofrece metodologías integrales y meticulosamente detalladas, diseñadas para ser totalmente reproducibles en la planificación y ejecución de la UGI a nivel de ciudad (Calaza Martínez, 2019). Este recurso de referencia aborda con precisión una amplia variedad de aspectos críticos relacionados con la funcionalidad y diseño de la UGI e introduce indicadores robustos destinados al control efectivo de estrategias de implementación de UGI. Es crucial reconocer el carácter innovador de esta guía, que se distingue por su aporte excepcional y ofrece una extensa gama de consideraciones para la implementación efectiva de infraestructura verde en entornos urbanos, estableciendo un precedente significativo en la gestión ambiental a nivel municipal.

Con estos marcos generales de referencia, la flexibilidad en la interpretación y aplicación práctica de la identificación y gestión de la UGI refleja adaptaciones diversas, según necesidades y contextos específicos. El estado del arte en infraestructura verde urbana revela ciertas limitaciones en los métodos de identificación, los cuales a menudo carecen de la manejabilidad y accesibilidad necesarias para especialistas y actores de diversos campos. Estos campos abarcan desde aspectos ecológicos o arquitectónicos hasta implicaciones psicosociales y socioeconómicas, consideraciones estéticas y hedónicas o inferencias relacionadas con el bienestar ciudadano (Kothencz et al., 2017; Shackleton et al., 2017; Votsis, 2017). Además, la clasificación de los elementos de infraestructura verde urbana cuenta con múltiples sistemas que suelen responder a criterios estructurales, basados en el tipo de componentes de cobertura y la configuración espacial de los elementos verdes, o criterios funcionales, que atienden fundamentalmente al tipo de uso del suelo (European Commission, 2016; Koc et al., 2016; Panduro and Veie, 2013). Esta diversidad de sistemas añade complejidad al ejercicio de estandarizar marcos de trabajo comunes entres disciplinas que sean manejables y reproducibles a escalas menores y que faciliten la integración efectiva de la UGI como un recurso consolidado en el contexto local (Cramer et al., 2018). Además, esta fragmentación metodológica subraya la necesidad de enfoques más integrados y abordables que permitan a las ciudades aprovechar plenamente los beneficios de la infraestructura verde urbana. Con todo ello, se pone de manifiesto la existencia de una carencia de herramientas transversales, accesibles, manejables, específicas y efectivas para promover la UGI en la planificación urbana estratégica orientada a la mitigación y adaptación de los impactos de las dinámicas climáticas actuales y futuras, especialmente en aquellas áreas geográficas más vulnerables a episodios extremos, como es el caso de la región mediterránea.

La presente tesis doctoral aborda, por un lado, la identificación y análisis de los elementos verdes públicos urbanos y periurbanos que pueden integrarse en una infraestructura verde a nivel local. Es de particular interés resaltar en este punto que las ciudades mediterráneas, particularmente afectadas por los impactos de las olas de calor, presentan características urbanas y arquitectónicas distintivas que comparten y que influyen en la implementación de medidas de adaptación frente a estos episodios extremos. Estas ciudades son compactas y se identifican por su densidad y complejidad urbanística (Muñoz, 2003). Su desarrollo se ha concentrado alrededor de núcleos históricos densamente poblados que han mantenido su configuración original a lo largo del tiempo (Rubiera Morollón et al., 2016). Esta preservación del patrimonio morfológico limita considerablemente la posibilidad de incorporar nuevas áreas verdes en los espacios intersticiales de la matriz urbana. Además, la estructura arquitectónica de los distritos centrales, compromete la existencia de áreas de UGI y dificulta la creación de nuevas zonas verdes (Haaland and Konijnendijk van den Bosch, 2015), reduciendo la resiliencia de las ciudades y su capacidad para contribuir al confort térmico durante episodios de temperaturas extremas (Gómez-Baggethun and Barton, 2013). En este contexto, se ha demostrado cómo la contribución de cada espacio verde, independientemente de su tamaño, se vuelve aún más influyente en el bienestar ciudadano y en la capacidad adaptativa del entorno urbano en términos de regulación térmica a nivel de sitio, entre otros beneficios (Battisti et al., 2019; Diappi, 2015; Matos et al., 2019; Pace et al., 2020).

Por otro lado, este estudio evalúa los servicios ecosistémicos de regulación que proporcionan las áreas de la UGI, enfocándose específicamente en la regulación de la temperatura urbana durante periodos de máximo estrés térmico, tales como las olas de calor, un fenómeno que es ya particularmente crítico en las ciudades mediterráneas. Para esta evaluación, se ha seleccionado la Temperatura Superficial del Suelo (LST, por sus siglas en inglés, *Land Surface Temperature*) como indicador. La LST es ampliamente utilizada en otros estudios para monitorizar y evaluar los efectos de las olas de calor en diferentes aspectos y a distintas escalas espaciales y temporales (Cotlier and Jimenez, 2022; Wei et al., 2022). De hecho, investigaciones previas a escala local han demostrado que valores altos de LST están directamente vinculados con un aumento en el riesgo de mortalidad y morbilidad durante estas condiciones extremas (Cuerdo-Vilches et al., 2023; Royé et al., 2020; Song et al., 2024). Para llevar a cabo estos análisis sobre la temperatura en superficie, las imágenes satelitales se han convertido en una herramienta cada vez más común en trabajos de investigación del ambiente térmico urbano, debido a su precisión en términos de resolución espacial (Lemus-Canovas et al., 2020). Es necesario puntualizar que en este estudio se ha considerado la LST como un buen indicador de la temperatura del aire a escala urbana. Aunque la LST y la temperatura del aire pueden mostrar ligeras diferencias en magnitud, la relación entre estas variables presenta una significancia estadística y unos patrones de distribución espacial alineados, lo que indica que áreas con alta LST coinciden con áreas de alta temperatura del aire (Benali et al., 2012; Coutts et al., 2016; Do Nascimento et al., 2022; Mutiibwa et al., 2015; Zhang et al., 2014). En este contexto, el rendimiento de las áreas de la UGI en términos de mitigación de altas temperaturas se interpreta a partir de la correlación entre la LST y el Índice de Vegetación de Diferencia Normalizada (NDVI, por sus siglas en inglés, *Normalized Difference Vegetation Index*), mostrando que una mayor capacidad de enfriamiento del área de la UGI se asocia con una correlación más negativa entre ambas variables (Keeratikasikorn and Bonafoni, 2018; Lemus-Canovas et al., 2020; Liu and Zhang, 2011; Vulova and Kleinschmit, 2019). A este respecto, se ha demostrado que las áreas verdes desempeñan un papel crucial en los entornos exteriores, mostrando correlaciones negativas y evidenciando su efectiva capacidad para mitigar las altas temperaturas y amortiguar los impactos durante episodios de temperaturas extremas (López-Bueno et al., 2020). De forma extendida, otros estudios evalúan los efectos y correlaciones en las zonas verdes a diversas escalas espaciales, generalmente abarcando superficies grandes, ciudades o regiones completas (Bartesaghi Koc et al., 2018). No obstante, también existen investigaciones que ofrecen perspectivas más detalladas dentro de los entornos urbanos al evaluar la LST empleando como referencia espacial las Zonas Climáticas Locales, definidas como "regiones de cobertura superficial uniforme, estructura, material y actividad humana que abarcan desde cientos de metros hasta varios kilómetros en escala horizontal" (Stewart and Oke, 2012).

A escala de sitio, la creación o mejora de espacios habitables (como patios o estructuras de sombreado) así como el aumento de espacios verdes con vegetación a nivel local y, en definitiva, las estrategias basadas en las NBS, ofrecen resultados significativamente positivos durante episodios de olas de calor (Diz-Mellado et al., 2021; Hidalgo-García and Arco-Díaz, 2022; Kumar et al., 2020; Natanian et al., 2020; Panagiotakis et al., 2021). En este sentido, la gestión de UGI destaca por la alta efectividad para acomodar determinadas zonas de la matriz urbana frente a los desafíos que plantean las futuras condiciones climáticas. No obstante, persiste la necesidad de realizar investigaciones adicionales para determinar los tipos de zonas, dentro de la propia UGI, más adecuados para áreas urbanas específicas, con el fin de fortalecer la capacidad de amortiguación contra los impactos de las olas de calor (Maggiotto et al., 2021; Santamouris and Osmond, 2020). Mientras que los parques urbanos de mayor tamaño exhiben usualmente una elevada capacidad para mejorar el confort térmico, los pequeños espacios verdes públicos urbanos destacan por su capacidad para extender los efectos de enfriamiento a una distancia relativa mayor que algunas áreas más extensas, lo que amplifica los beneficios que estos generan a nivel de micrositio, como dentro de barrios o agrupaciones residenciales (Gallay et al., 2023; Peng et al., 2021). Estos espacios verdes de menor tamaño tienen el potencial de reducir significativa y efectivamente la LST en sus alrededores, contribuyendo a la mejora del entorno térmico urbano, particularmente ciudades compactas (Wu et al., 2021).

En consonancia con todo lo expuesto, los objetivos de esta tesis se centran en identificar y clasificar los elementos de la UGI mediante un protocolo escalable y transferible, analizar qué tipo de zonas amortiguan mejor los impactos de las olas de calor y, entre las áreas que mejor mitigan el estrés térmico durante estos episodios extremos, determinar qué elementos de composición superficial y qué tipos de áreas, en función de sus componentes, reducen la probabilidad de alcanzar mayores valores de LST. El valor añadido de este estudio al conocimiento existente en la materia reside en evaluar el rendimiento específico de distintos tipos de áreas de la UGI como unidades individuales, lo cual es clave para analizar en detalle qué componentes estructurales y tipologías de áreas presentan mayor efectividad en la mitigación de las olas de calor dentro de la matriz urbana y, en definitiva, para contribuir de forma pragmática a una planificación urbanística resiliente al contexto climático actual y futuro.

2. Objetivos.

A continuación, se detallan los objetivos planteados en la presente tesis doctoral:

1. Identificar los principales elementos verdes (núcleos, nodos y conectores) distribuidos por el área urbana y periurbana susceptibles de integrarse en una infraestructura verde urbana (UGI), estableciendo un proceso de identificación que maximice la superficie verde funcional para la mejora del aprovisionamiento de servicios ecosistémicos a nivel urbano y de sitio.

2. Consolidar la UGI identificada a través de la propuesta de incorporación de nuevos elementos verdes con capacidad para contribuir de forma activa en el aprovisionamiento de servicios ecosistémicos.

3. Elaborar un protocolo escalable y transferible, que promueva y facilite la identificación de la UGI en entornos urbanos mediterráneos, estableciendo criterios claros basados en la distribución espacial, extensión y capacidad de proporcionar servicios ecosistémicos.

4. Evaluar la capacidad de los tipos de áreas de la infraestructura verde urbana para amortiguar los impactos de las olas de calor en ciudades compactas mediterráneas, mediante el análisis de la temperatura superficial del suelo (LST) y el índice de vegetación de diferencia normalizada (NDVI).

5. Identificar los patrones de composición superficial de las áreas de la infraestructura verde urbana con mejor rendimiento en términos de amortiguación de los impactos de las olas de calor en la región mediterránea.

6. Evaluar la asociación y la fuerza explicativa entre la variación de los valores de temperatura superficial del suelo durante episodios de olas de calor y los elementos de composición y tipos de áreas con mejor rendimiento en términos de amortiguación de los impactos de las olas de calor en la región mediterránea.

8. Identificar las limitaciones del estudio y establecer líneas futuras de investigación, prácticas y ágiles, que garanticen la continuidad de los hallazgos de este trabajo, para profundizar el conocimiento y mejorar la gestión de la UGI dentro del marco de la planificación urbanística, permitiendo así un enfoque más exhaustivo y efectivo considerando las dinámicas climáticas actuales y futuras.

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CAPÍTULO 2. MATERIAL Y MÉTODOS

1.- Información general sobre el área de estudio.

La ciudad de Granada (37.179937, -3.603489; 680 metros sobre el nivel del mar) está ubicada en el sureste de la Península Ibérica, con una extensión de 88.9 km2, de acuerdo con los datos espaciales de referencia de Andalucía – DERA ("Datos Espaciales de Referencia de Andalucía (DERA) - Conjuntos de datos | Portal de datos abiertos," n.d.) (Figura 1). El área de estudio es representativa de una ciudad compacta de tamaño medio en la región mediterránea si se atiende a su rango de población (entre 200,000 y 500,000 habitantes), densidad de población (2657.93 habitantes/Km^2), la alta contigüidad y proximidad de sus unidades habitacionales en los distritos, la clara separación existente entre el uso urbano y rural en la periferia de la ciudad, y la accesibilidad a la mayoría de los servicios locales a pie o en transporte público (OECD, 2012; "Population by region - Urban population by city size - OECD Data," n.d., "Spanish Statistical Office," n.d., "Spanish Urban Agenda," n.d.). En el área urbana de Granada, se puede observar una cobertura excesiva de áreas urbanizadas, con un aumento del 12.42% entre 2002 y 2022 (Hidalgo-García and Arco-Díaz, 2022). El porcentaje promedio del área urbanizada en 2022 varió desde el 39.37% en distritos periféricos hasta el 87.28% en los distritos céntricos (Hidalgo García, 2023).

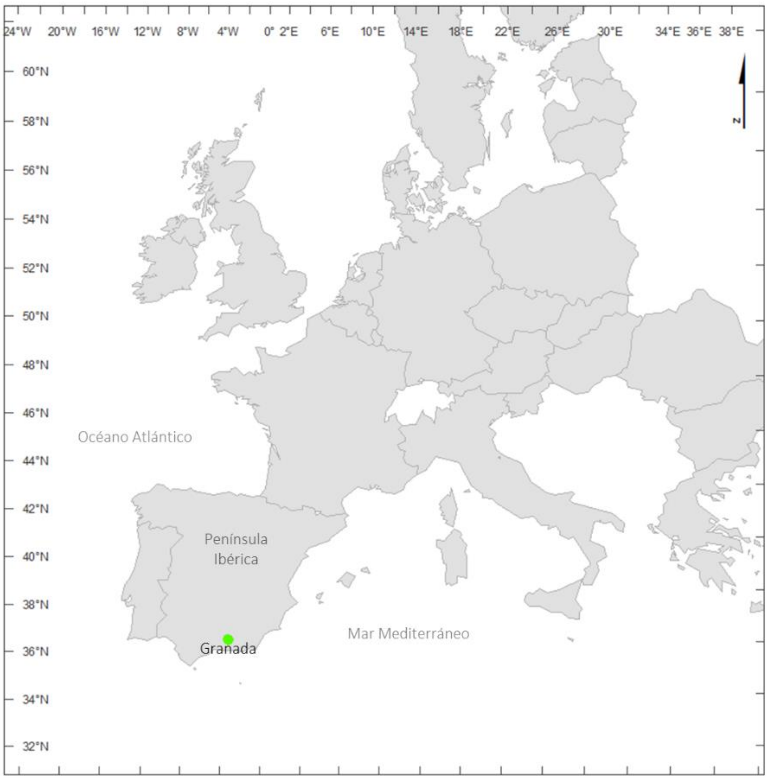

Figura 1. Localización del área de estudio.

La clasificación climática de Köppen-Geiger para Granada es Csa, lo que corresponde a un clima mediterráneo caracterizado por veranos secos y calurosos (Andrade and Contente, 2020; "World Maps of Köppen-Geiger climate classification," n.d.). El área de estudio presenta un clima mediterráneo-continental, con registros durante el periodo 1984 - 2014 de una temperatura media anual de 15.2 °C, un promedio de 2 días anuales de calor (temperaturas iguales o superiores a los 40 °C) y precipitación anual media de 365.3 mm. (Figura 2). De cara al periodo 2021-2050, las proyecciones para esta misma zona indican un aumento en la temperatura media anual hasta los 16.8 °C, un incremento a aproximadamente 8 días de calor por año y una reducción en las precipitaciones anuales a 340.3 mm ("Clima de Andalucia," n.d.). Granada se ubica en el sector de la región mediterránea con mayor frecuencia de olas de calor y frío en las últimas décadas (Cuadrat et al., 2013; Tomczyk et al., 2017). En concreto, el municipio ha estado desde el año 1975 significativamente impactado por episodios de temperaturas extremas, exhibiendo la mayor tasa de recurrencia de estos eventos desde 2011 (AEMET, 2023). Además, Granada registra unos rangos elevados de amplitud térmica, más acusada en los meses de verano, debido a su localización geográfica en la depresión formada por el río Genil, dentro del valle de la cordillera de Sierra Nevada (Cariñanos et al., 2014).

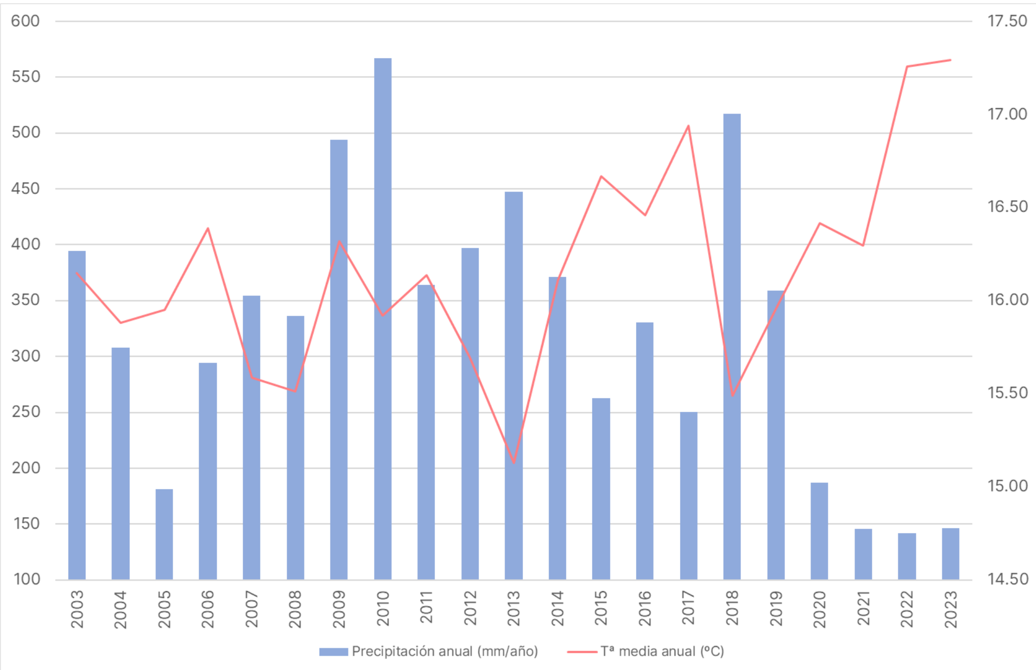

Figura 2. Datos climatológicos del área de estudio: temperatura media anual y precipitación anual. Serie 2003-2023. Fuente: AEMET Open Data ("AEMET OpenData - Agencia Estatal de Meteorología - AEMET. Gobierno de España," n.d.).

2.- Protocolo estandarizado para la identificación de la infraestructura verde urbana.

El enfoque conceptual del protocolo establecido para la identificación de la infraestructura verde urbana, UGI (por sus siglas en inglés, *Urban Green Infraestructure*), está en línea con los principios fundamentales para la planificación de espacios verdes públicos en las ciudades. Estos principios se apoyan en la integración de elementos clave dentro de la matriz urbana; la conectividad entre los espacios verdes identificados; la multifuncionalidad de estas áreas para mejorar la capacidad adaptativa de la ciudad al estrés climático; y la inclusión social, permitiendo la identificación de aquellas áreas urbanas con mayor necesidad de espacios verdes (Santos, 2016). Así, el protocolo de identificación desarrollado se ajusta a la distribución espacial de las áreas verdes, su tamaño y su potencial para ofrecer servicios ecosistémicos, contribuyendo a la mejora del bienestar de la ciudadanía y al fortalecimiento de la resiliencia frente al cambio climático.

Para la identificación de zonas verdes susceptibles de formar parte de la UGI, se emplearon datos sobre uso del suelo provenientes de diversas fuentes de información cartográfica. Es necesario mencionar que el primer ejercicio de identificación se realizó en el año 2017, como actividad precursora al primer manuscrito del presente compendio. Se utilizó el conjunto de datos de CORINE (Coordination of Information on the Environment) Land Cover, el cual proporciona una clasificación detallada de la cobertura del suelo a nivel europeo ("Copernicus Land Monitoring Service - Corine Land Cover — European Environment Agency," n.d.). Además, se recurrió al Sistema de Información sobre Ocupación del Suelo de España (SIOSE) del año 2016, disponible a una escala de 1:10,000 y actualizado en 2021 (Spanish National Geographic Institute, 2021), ofreciendo una visión detallada de la ocupación del suelo a nivel nacional. De forma complementaria, se consultó la Red de Información Ambiental de Andalucía (REDIAM) ("Red de Información Ambiental de Andalucía - Portal Ambiental de Andalucía," n.d.), que ofrece información específica sobre zonas verdes públicas de las capitales de provincia de Andalucía y de los municipios con más de 100,000 habitantes, todo ello a una escala de 1:5,000 y con la última revisión realizada en 2016 ("Red de Información Ambiental de Andalucía - Portal Ambiental de Andalucía," 2023). Aunque no se han observado cambios significativos en el número de áreas identificadas tras las actualizaciones de las fuentes de información mencionadas, es importante destacar que algunos espacios han sido añadidos manualmente desde el año 2019, por lo que la base de datos empleada ha sido revisada y actualizada con regularidad hasta marzo de 2023.

En primer lugar, la definición de los elementos a incluir en la UGI consideró la capacidad de las áreas verdes urbanas para proporcionar servicios ecosistémicos, poniendo especial interés en la contribución a la resiliencia urbana en términos de mitigación de los efectos del cambio climático. Para ello, se identificaron áreas en la ciudad de Granada con usos del suelo especialmente activos en la provisión de servicios ecosistémicos de regulación, tales como la mejora de la calidad del aire, el potencial de enfriamiento de ambientes urbanos o la mitigación del efecto de isla de calor, entre otros (Dige et al., 2014; Maes et al., 2011). De forma cualitativa, se asignó una capacidad alta o media para proporcionar servicios ecosistémicos a los usos del suelo correspondientes a parques y bosques urbanos, zonas urbanas y peri-urbanas de cultivos heterogéneos o pastizales naturales continuos. Por otro lado, las coberturas del suelo con presencia de matorrales dispersos y pastizales continuos no se consideraron tan activos en términos de provisión de servicios ecosistémicos, presentando exclusivamente una capacidad media o baja para hacerlo (Burkhard et al., 2009; Depellegrin et al., 2016; Graça et al., 2018; Mexia et al., 2018; Vihervaara et al., 2010).

En segundo lugar, una vez definidas las áreas verdes públicas susceptibles de formar parte de la UGI, se seleccionaron aquellos espacios ubicados dentro del límite administrativo de la ciudad (áreas urbanas) o inmediatamente adyacentes a este (áreas periurbanas). Las áreas que cumplían con los criterios mencionados anteriormente y que no aparecían en ninguna fuente de información, fueron manualmente agregadas a la cartografía. Finalmente, las áreas definidas y seleccionadas se clasificaron según su distribución espacial en la matriz urbana, entendiendo la configuración de espacios como una red compuesta por centros funcionales y enlaces dispersos que los conectan a través del paisaje urbano (Benedict and McMahon, 2000).

Tras llevar a cabo la definición, selección y clasificación de las áreas verdes, el protocolo de categorización resultante definió 4 tipos de espacios verdes urbanos y periurbanos en función de su extensión, ubicación y capacidad para proporcionar servicios ecosistémicos (Figura 3):

- Áreas "*Core*" (núcleo): se definen como áreas de gran tamaño (más de 100,000 m²) con una alta capacidad para proporcionar servicios ecosistémicos de regulación, de aprovisionamiento y culturales, como parques naturales o bosques urbanos.
- Áreas "*Node*" (nodo): se definen como espacios de tamaño medio (rango de extensión entre 10,000 m² y 100,000 m² y algunas excepciones por debajo de los 10,000m² ubicadas en el distrito centro de la ciudad), con una alta capacidad para proporcionar servicios ecosistémicos, tales como parques, jardines y plazas, o pequeños bosques, matorrales densos o pastizales.
- Áreas "*link*" (conectores): son aquellas con distribución espacial lineal que enlazan núcleos y nodos y suelen corresponder con avenidas y paseos provistos de vegetación, en su mayoría, de porte arbóreo.
- Áreas "*Other*": también conocidas como SPUGS (por sus siglas en inglés, *Smaller Public Urban Green Spaces*) (Peschardt et al., 2012). Engloban pequeños espacios verdes públicos urbanos con una extensión generalmente inferior a 10,000 m², distribuidos de forma heterogénea a través del entorno urbano y con capacidad de brindar tanto servicios ecosistémicos culturales como de regulación. Estos espacios suelen corresponder con pequeños parques y plazas que combinan distintos elementos de composición superficial. También pueden incluir zonas arbustivas densas o dispersas, superficies con cobertura herbácea, áreas que combinan vegetación de porte medio y bajo, así como zonas peatonales de tránsito y grupos aislados de árboles.

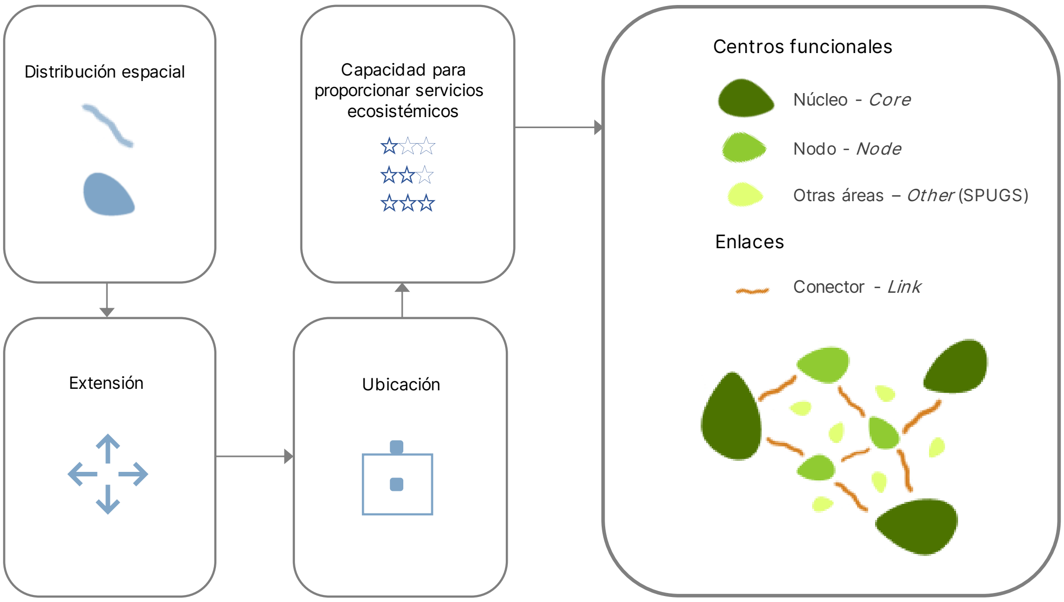

Figura 3. Esquema del protocolo establecido para la categorización de los elementos de infraestructura verde urbana.

Adicionalmente, se llevó a cabo una evaluación inicial sobre la disponibilidad y accesibilidad de la infraestructura verde urbana. Para ello, se obtuvieron los datos de superficie y población del registro municipal de habitantes de 2017 correspondientes a los 31 barrios de la ciudad de Granada ("Granada Town Hall Website," 2019). La disponibilidad de espacios verdes se calculó en base a la superficie de UGI por habitante en cada barrio. Por otro lado, la accesibilidad se evaluó calculando la distancia como medida simple desde cualquier punto del tejido urbano al área verde más próxima identificada dentro de la UGI (Halden et al., 2000; Silva et al., 2018).

3.- Determinación de la capacidad de amortiguamiento de áreas de la UGI durante olas de calor.

3.1.- Registros de olas de calor.

La definición de "ola de calor" utilizada en este estudio corresponde a la proporcionada por la Agencia Estatal de Meteorología (AEMET) de España. Según la AEMET, una ola de calor se define como un episodio que dura 3 días consecutivos o más, durante el cual al menos el 10% de las estaciones meteorológicas registran temperaturas máximas por encima del percentil 95 de su serie de temperaturas máximas diarias para los meses de julio y agosto del período 1971 a 2000 (Spanish Agency of Meteorology, 2022). El período considerado para este estudio abarca desde 2017 hasta 2023, es decir, desde la definición de la infraestructura verde urbana (UGI) en la ciudad de Granada hasta el último episodio registrado con datos disponibles para el año 2023 ("Olas de calor en España desde 1975 - Agencia Estatal de Meteorología - AEMET. Gobierno de España," n.d.) (Tabla 1).

3.2.- Estimación de la temperatura superficial del suelo y el índice de vegetación de diferencia normalizada.

La Temperatura de la Superficie Terrestre, LST (por sus siglas en inglés, *Land Surface Temperature*), es la temperatura radiativa de la capa superficial del terreno. Es un parámetro que mide la emisión de radiación térmica desde la superficie terrestre, en la que elementos como el suelo o el dosel de la vegetación se calienta por el efecto de la energía solar (Khan et al., 2021; "Land surface temperature and thermal infrared emissivity," 2020). El índice de vegetación de diferencia normalizada, NDVI (por sus siglas en inglés *Normalized Difference Vegetation Index*) es un índice de teledetección ampliamente utilizado y reconocido que se emplea para cuantificar el verdor y la densidad de la vegetación así como para evaluar cambios en la salud de las plantas ("Landsat Normalized Difference Vegetation Index | U.S. Geological Survey," n.d.). Para llevar a cabo la estimación de ambos parámetros se realizó una meticulosa recolección de datos a partir de imágenes satelitales OLI/TIRS correspondientes a los satélites Landsat 8 y 9, obtenidas a través del Servicio Geológico de los Estados Unidos ("Landsat Normalized Difference Vegetation Index | U.S. Geological Survey," n.d.). La idoneidad de las escenas de Landsat en este tipo de investigación se debe principalmente a su resolución temporal (cada 16 días), resolución espacial y la probabilidad de obtener una cobertura mínima de nubes (Grigoraș and Urițescu, 2019; Naserikia et al., 2019; "USGS.gov | Science for a changing world," n.d.). El ajuste de estas variables resultó esencial para garantizar la precisión y la viabilidad en la estimación de los valores de NDVI y LST y, en consecuencia, para el análisis y la interpretación de la dinámica y las variaciones de temperatura sobre las áreas de infraestructura verde urbana.

A lo largo del estudio, se identificaron un total de 16 episodios de olas de calor. Sin embargo, fue posible realizar la obtención de datos de NDVI y LST únicamente en 11 de ellos. Esta limitación fue debida a la ausencia ocasional de imágenes de Landsat en las fechas requeridas, así como a la interferencia con la presencia de nubes, lo que imposibilitó el cálculo adecuado de la LST y el NDVI sobre las áreas de infraestructura verde dentro de la matriz urbana (Tabla 1).

Episodios de olas de calor (HW [1])	Fechas de Inicio-Fin	Duración	Fuente [2]	Toma de datos	
				Fecha	Hora (GMT+1) [3]
HW 1	13–21 June 2017	9 días	Landsat 8 (OLI/TIRS)	19 junio 2017	11:49:55
HW 2	12–16 July 2017	5 días	Landsat 8 (OLI/TIRS)	No disponible en fechas requeridas	
HW 3	28–30 July 2017	3 días	Landsat 8 (OLI/TIRS)	No disponible en fechas requeridas	
HW 4	2–6 August 2017	5 días	Landsat 8 (OLI/TIRS)	Cobertura de nubes sobre núcleo urbano	
HW 5	31 July–7 August 2018	8 días	Landsat 8 (OLI/TIRS)	9 agosto 2018	11:49:50
HW 6	26 June–1 July 2019	6 días	Landsat 8 (OLI/TIRS)	25 junio 2019	11:50:04
HW 7	20–25 July 2019	6 días	Landsat 8 (OLI/TIRS)	18 julio 2019	11:56:19
HW 8	25 July–2 August 2020	9 días	Landsat 8 (OLI/TIRS)	29 julio 2020	11:50:08
HW 9	6–8 August 2020	5 días	Landsat 8 (OLI/TIRS)	5 agosto 2020	11:56:20
HW 10	11–16 August 2021	6 días	Landsat 8 (OLI/TIRS)	17 agosto 2021	11:50:21
HW 11	12–18 June 2022	7 días	Landsat 9 (OLI/TIRS)	9 junio 2022	11:49:43
HW 12	9–26 July 2022	18 días	Landsat 8 (OLI/TIRS)	19 julio 2022	11:50:28
HW 13	9–12 July 2023	4 días	Landsat 8 (OLI/TIRS)	No disponible en fechas requeridas	
HW 14	17–20 July 2023	4 días	Landsat 8 (OLI/TIRS)	Cobertura de nubes sobre núcleo urbano	
HW 15	6–13 August 2023	8 días	Landsat 8 (OLI/TIRS)	7 agosto 2023	11:50:03
HW 16	17–25 August 2023	9 días	Landsat 8 (OLI/TIRS)	23 agosto 2023	11:50:11

Table 1. Información sobre Olas de calor registradas e imágenes satelitales Landsat empleadas. 1: HW#: Episodio de ola de calor; 2: OLI/TIRS: Operational Land Imager Thermal Infrared Sensor; 3: GMT: Global Meridian Time.

El índice de vegetación de diferencia normalizada (NDVI) se calculó utilizando el sensor OLI (*Operational Land Image*) para el espectro de luz visible y el infrarrojo cercano de los satélites Landsat 8 y 9. El cálculo del NDVI se basa en la diferenciación entre la reflectancia observada en la banda del rojo (R, banda 4) y la banda del infrarrojo cercano (NIR, banda 5) (Ecuación 1):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{R})}{(\mathrm{NIR} + \mathrm{R})} \quad (1)$$

NIR representa la reflectancia en la banda del infrarrojo cercano y R la reflectancia en la banda del rojo. Esta fórmula cuantifica la densidad de la vegetación en una escala que varía de -1 a +1, donde valores cercanos a +1 indican una alta densidad de vegetación y valores cercanos a 0 o negativos reflejan la ausencia de vegetación o superficies no vegetativas, como agua, nubes o áreas urbanas construidas.

La temperatura superficial del suelo (LST) se calculó mediante un algoritmo mejorado para la obtención automatizada de la temperatura de la superficie terrestre a partir de los datos de la banda del sensor térmico de infrarrojos (TIRS) de los satélites Landsat 8 y 9 (Avdan and Jovanovska, 2016; Jiménez-Muñoz et al., 2014; Sheik Mujabar, 2019; Sobrino et al., 2004; Stathopoulou and Cartalis, 2007; Wang et al., 2015) (Ecuación 2):

$$\mathrm{LST} = \frac{\mathrm{BT}}{\{1 + \left[\left(\frac{\lambda \mathrm{BT}}{\rho}\right) ln\varepsilon_{\lambda}\right]\}} \quad (2)$$

Donde:

BT = Temperatura de brillo,

λ = Longitud de onda de la radiación emitida (Banda 10 de Landsat 8 y 9), 10.8 μm.

ρ = h × c / **σ** = 1.4388×10^{-2} mK (h = constante de Planck = 6.626×10^{-34} J s, c = velocidad de la luz = 2.998×10^{8} m/s y **σ** = constante de Boltzmann = 1.38×10^{-23} J/K).

ε_{λ} = emisividad de la superficie terrestre.

Por último, es necesario destacar la validación del método empleado, así como la precisión de las estimaciones proporcionadas para calcular tanto el NDVI como la LST. Los datos de NDVI y LST derivados de los sensores OLI (banda 4, roja; banda 5, infrarroja cercana) y TIRS (banda 10) demostraron ser precisos y coherentes con las propiedades de las áreas estudiadas, confirmando la solidez y exactitud de las imágenes Landsat para estos análisis específicos (Cook et al., 2014; Jiménez-Muñoz et al., 2014). Adicionalmente, la consideración de los rangos de longitud de onda y las respuestas espectrales diferenciadas para la emisividad según el componente de superficie, confirmaron la efectividad del algoritmo empleado para la obtención de la LST a partir de Landsat 8 y 9 (Tan et al., n.d.; Yu et al., 2014). La rigurosidad del enfoque metodológico para la obtención, tratamiento y análisis de datos relevantes facilitó la generación de evaluaciones precisas sobre las dinámicas de la LST en relación con el NDVI, los distintos tipos de áreas de la UGI y sus elementos de composición superficial. De esta manera, se consiguió proporcionar una visión más granular de cómo la tipología y composición de las áreas de la UGI pueden contribuir a atenuar los efectos derivados de los episodios de olas de calor.

3.3.- Composición y tipología de áreas identificadas como "Other" (SPUGS).

Para llevar a cabo el análisis de composición de las áreas categorizadas como "Other", también definidas como SPUGS (por sus siglas en inglés, *Small Public Urban Green Spaces*) se realizó la identificación de sus elementos de superficie, tanto naturales como construidos. Dentro de estos elementos se incluyeron árboles y arbustos, superficies con cobertura herbácea, así como suelo desnudo. Además, se consideraron tanto superficies permeables (tierras estabilizadas que pueden estar compuestas por arenas o limos entre otros materiales), como pavimentos impermeables (asfalto, cemento, baldosas de construcción y superficies derivadas del caucho). De forma complementaria, se incorporaron estructuras edificadas y elementos con agua (correspondiendo principalmente con pequeñas fuentes ubicadas en las plazas). Además, se incluyeron como elemento estructural de superficie aquellos pavimentos semipermeables de alto albedo compuestos por distintos tipos de empedrado (tales como guijarros, adoquines, cantos rodados o gravas) con espacios porosos intersticiales. Estos pavimentos son una seña de identidad de los parques y plazas urbanas en la región mediterránea, siendo testimonio de su legado histórico y cultural, por lo que se consideró como un tipo de cobertura con entidad propia, distintiva y representativa del paisaje urbano (Figura 4).

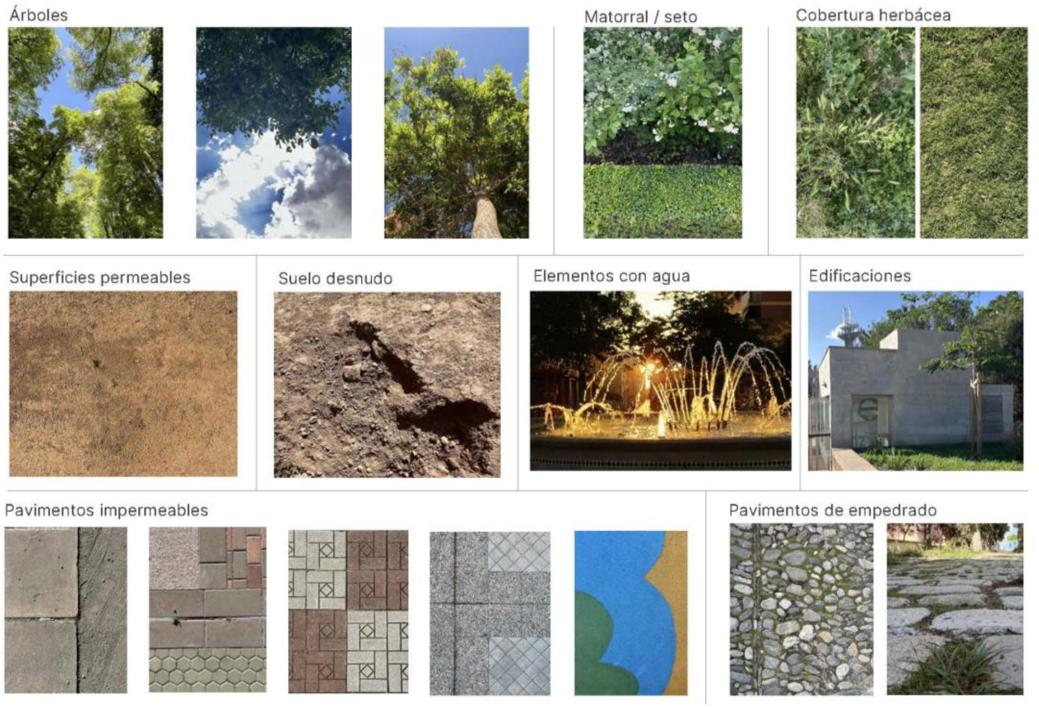

Figura 4. Ejemplos de elementos de composición superficial considerados en las áreas definidas como SPUGS.

Para refinar la clasificación este tipo de áreas, se llevó a cabo un proceso de agrupación utilizando la técnica de *clustering* "K-means", un enfoque especialmente útil para identificar grupos naturales dentro de un conjunto de datos, que añade un centro de clúster a la vez mediante un procedimiento de búsqueda global determinista (Likas et al., 2003). Este método fue empleado específicamente para identificar y categorizar los tipos de áreas en base a la presencia de elementos de composición superficial. Al agrupar las variables de esta manera, se logró una segmentación clara y efectiva de los SPUGS, permitiendo distinguir entre diferentes grupos que comparten características comunes en sus superficies. Este enfoque analítico facilitó una comprensión más detallada de la diversidad y las propiedades específicas de los SPUGS, ofreciendo una perspectiva práctica en la clasificación de estos espacios dentro del tejido urbano. La agrupación resultó en cuatro tipos distintos definidos por sus elementos de composición (Figura 5):

- Plazas y parques tradicionales (TSQ) caracterizados por la presencia de pavimentos semipermeables de alto albedo, principalmente empedrados compuestos por adoquines de colores claros, grava, cantos rodados o guijarros. Además, estos espacios cuentan con la presencia de árboles y pequeñas áreas de jardín dispersas con arbustos.

- Áreas de parques y jardines (PPG) principalmente ocupadas por árboles, arbustos, setos ajardinados y una combinación de pavimentos impermeables y permeables. Además, estas áreas pueden incluir zonas de recreo (áreas de juego), senderos o caminos de corta distancia o pequeñas superficies para uso deportivo.

- Áreas peatonales y de tránsito (PIT) distribuidas por toda la ciudad, caracterizadas por una combinación de árboles y pavimentos predominantemente impermeables como, baldosas, hormigón, asfalto, superficies derivadas del caucho y otros pavimentos similares.

- Áreas verdes principalmente compuestas de vegetación herbácea (HVP) con presencia de árboles y arbustos dispersos. Estas zonas incluyen parques públicos además de áreas con fines ornamentales o estructurales.

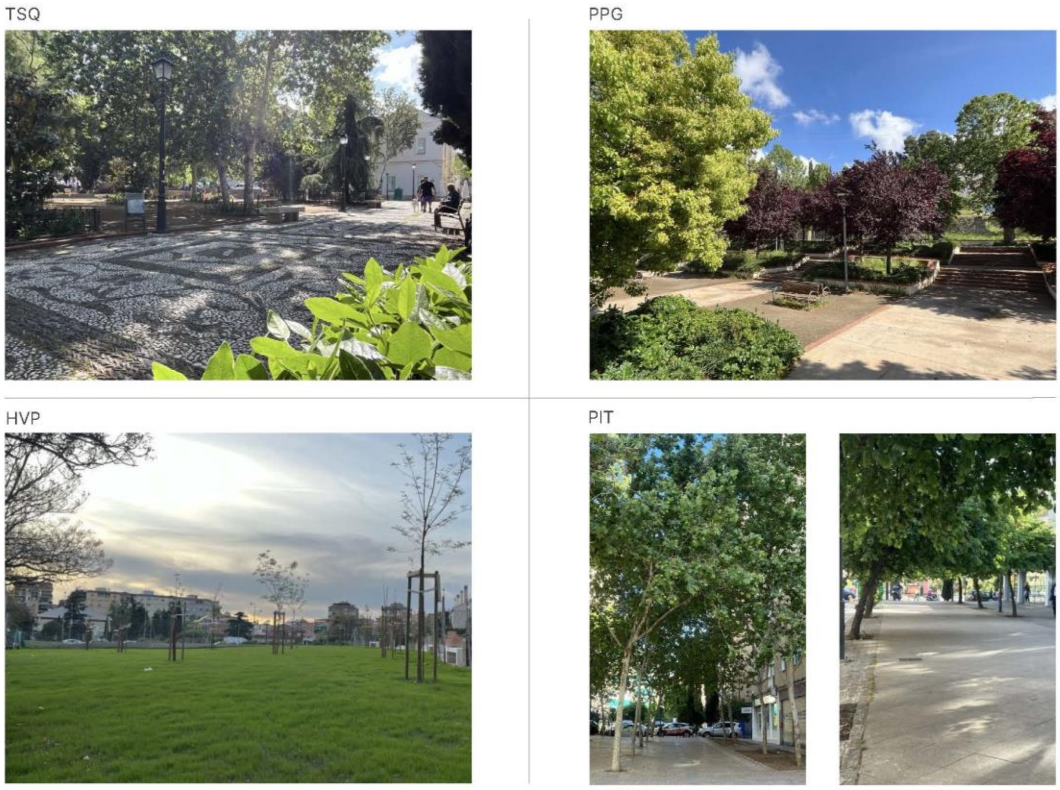

Figura 5. Ejemplos de tipos de SPUGS en base a sus elementos de composición. Plazas y parques tradicionales (TSQ), áreas de parques y jardines (PPG), áreas verdes principalmente compuestas de vegetación herbácea (HVP), áreas peatonales y de tránsito (PIT).

4. Tratamiento y análisis de datos

Para la realización de tareas cartográficas tales como la creación y edición de mapas, y tratamiento y análisis de datos espaciales necesarios para la identificación y representación cartográfica de las áreas de la UGI, se utilizó el software ARCGIS 10.6. En particular, la obtención de los valores de LST y NDVI se realizó a través de operaciones matemáticas y lógicas en capas ráster a partir de imágenes Landsat dentro del propio software. Además, el uso de herramientas para generar estadísticas zonales permitió la exportación de datos de LST y NDVI a un formato apropiado para su posterior análisis estadístico, permitiendo así un tratamiento eficaz de los datos en la evaluación cuantitativa. Por último, la identificación de los elementos de composición de las áreas seleccionadas dentro la de la UGI se realizó calculando el porcentaje de cobertura para cada elemento de composición, un ejercicio clave para entender la estructura y funcionalidad de las áreas filtradas de la UGI en ese punto del estudio. La base de datos de UGI se actualizó con los últimos datos vectoriales geoespaciales proporcionados por el sistema nacional de cobertura del suelo (SIOSE) para 2016 a una escala de 1:10,000, publicado en 2021 (Spanish National Geographic Institute, 2021).

Para el análisis estadístico, se abordaron dos aspectos principales. Por un lado, se analizó la correlación entre LST y NDVI, con objeto de identificar aquellos tipos de área dentro de la UGI con mayor potencial de amortiguar los impactos derivados de las olas de calor en entornos urbanos (Keeratikasikorn and Bonafoni, 2018; Lemus-Canovas et al., 2020; Liu and Zhang, 2011; Vulova and Kleinschmit, 2019). Se evaluó la distribución de la muestra de valores obtenidos con la prueba de Kolmogórov-Smirnov para ambas variables, LST y NDVI. Consecuentemente, se calculó el coeficiente de correlación de Spearman ($p < 0.05$) entre los valores obtenidos de LST y NDVI (en todos los episodios de olas de calor, para eventos separados y para cada tipo de área UGI. Dado que solo se registró un tipo de área núcleo dentro del límite urbano (Bosques de la Alhambra), se excluyó de los análisis estadísticos. Los cálculos se llevaron a cabo utilizando el software MATLAB R2020b.

Por otro lado, y tras determinar qué tipo de áreas dentro de la UGI presentaron una mayor capacidad de refrigeración en entornos urbanos durante episodios de olas de calor (identificadas como SPUGS), se procedió a examinar la asociación, dirección y fuerza de determinadas variables en el poder explicativo para alcanzar ciertos rangos de LST en cada evento de ola de calor. Para ello, se realizaron regresiones ordinales con el fin de analizar el efecto de los componentes superficiales de las SPUGS, orientación y tipología de área verde (como variables independientes) en los rangos de LST alcanzados (como variables dependientes). Se modelaron 12 regresiones ordinales múltiples, una para cada episodio de ola de calor con datos disponibles y otra con el valor medio de todos los episodios en conjunto. Este enfoque permitió evaluar el efecto de las características físicas y estructurales de los SPUGS en la modulación de la LST en el contexto urbano de la ciudad de Granada durante los episodios de calor acontecidos entre los años 2017 y 2023. Para valorar los niveles de poder explicativo de los modelos utilizados en comparación con el modelo nulo, se recurrió a las medidas pseudo R-cuadrado de Cox y Snell, Nagelkerke y McFadden. El análisis estadístico de esta sección del estudio se llevó a cabo utilizando el software IBM SPSS Statistics, versión 28.0.0.0.

La selección de este análisis estadístico residió en la naturaleza ordinal inherente de las variables dependientes, creadas al recodificar porcentajes de cobertura y valores de LST por rangos. La regresión lineal, diseñada para variables dependientes continuas, y la regresión logística, adaptada para resultados binarios, no capturarían con tanta precisión la naturaleza ordenada de las variables consideradas. Es por ello por lo que la regresión ordinal resultó particularmente apropiada para las preguntas originadas en este tramo de la investigación, dada su capacidad para manejar categorías ordenadas y alinear de manera coherente los datos a analizar, así como la interpretación de los mismos (Valle et al., 2019). Además, el modelo de regresión ordinal generalmente muestra un ajuste robusto y habilidad predictiva fuera de muestra en comparación con modelos alternativos al trabajar con distribuciones discretas. Su efectividad puede resultar aún más pronunciada cuando se trata con límites superiores e inferiores claramente definidos para las categorías, como es el caso (Williams and Quiroz, 2020). Este enfoque matizado para abordar el análisis estadístico, acomodando categorías ordenadas, permitió capturar la esencia de las variaciones y distribuciones de LST durante los episodios de olas de calor con datos disponibles, demostrando un buen ajuste y una capacidad predictiva significativa, en línea con investigaciones previas específicas para el clima mediterráneo (Pantavou and Lykoudis, 2014).

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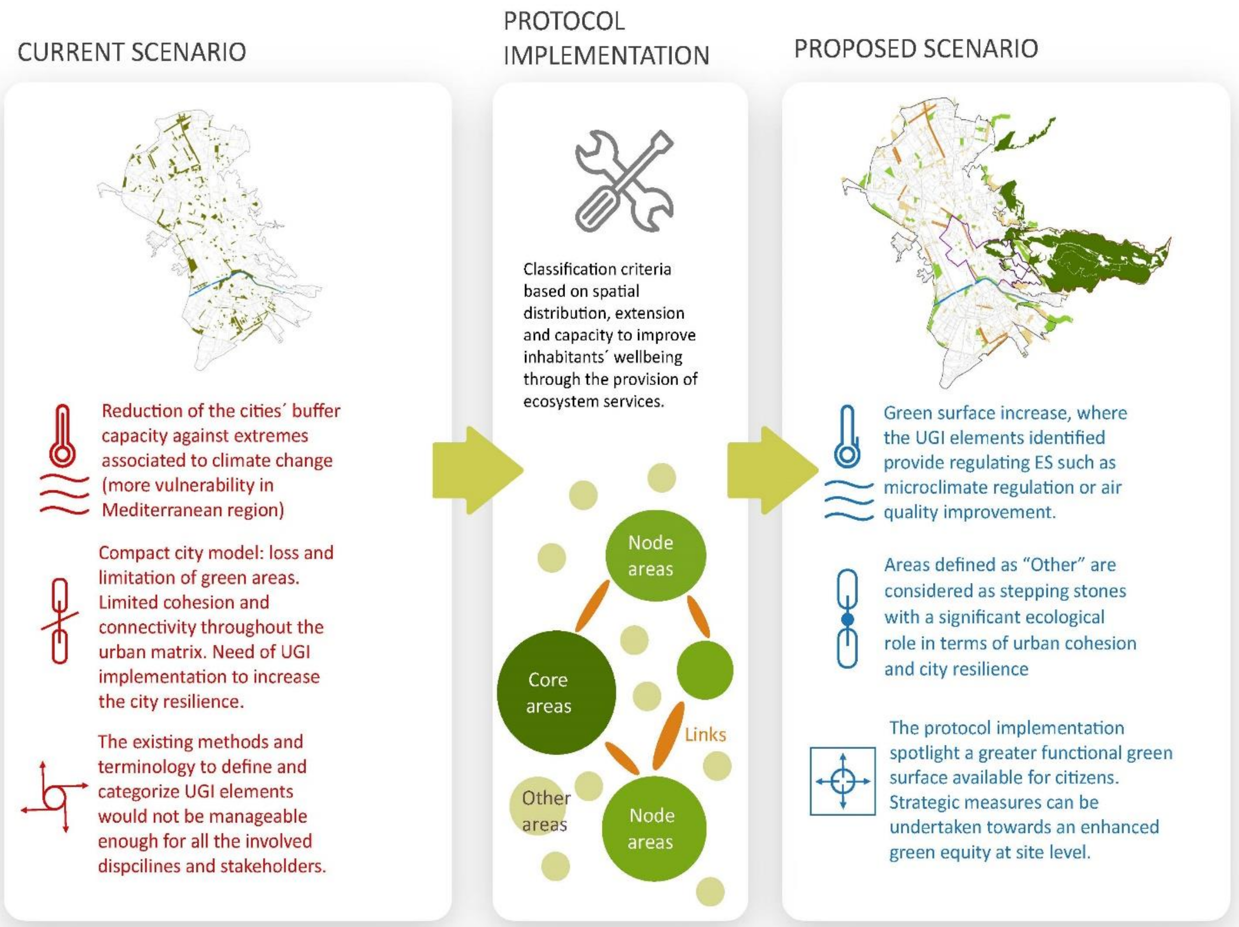
CAPÍTULO 3. RESULTADOS

3.1. Towards a standard framework to identify green infrastructure key elements in dense Mediterranean cities.

Revista: Forests, 2020.
Volumen: 11(12):1246
DOI: https://doi.org/10.3390/f11121246
URL: https://www.mdpi.com/1999-4907/11/12/1246
Autores: Manuel José Delgado-Capel, Paloma Cariñanos

Graphical abstract



Abstract

Present-day dense cities are increasingly affected by the impacts associated to climate change. The recurrence of extreme climate events is projected to be intensified in cities in the next decades, especially in the most vulnerable areas of the world, such as the Mediterranean region. In this context, the Urban Green Infrastructure (UGI) is presented as a nature based solution, that directly contributes to climate change mitigation in Mediterranean compact cities and improves health, social, welfare and environmental conditions for inhabitants. This research sets out a manageable framework to define, locate, and categorize more functional green urban and peri-urban areas in a dense Mediterranean city. It takes spatial distribution, extension, and the capacity to improve inhabitants´ wellbeing through the provision of ecosystem services as classification criteria. Results show a scenario with a greater functional green surface available for the citizens to be managed. Identified areas have been categorized as cores, nodes, links, and green spaces defined as "Other" areas. In particular, the latter play a significant role at social, structural, and ecological level. The study showcases that rethinking urban design and strategic decision-making around these areas can enhance green equity in Mediterranean dense cities, their capacity to better deal with environmental extremes and the inhabitants´ engagement with a culture of sustainability and wellbeing.

1. Introduction

Climate change mitigation and adaptation are two of the main challenges faced by present-day urban environments, where densification is becoming even greater. According to the United Nations World Urbanization Prospects, 68% of the world´s population will live in urban areas by 2050 (Developments and Forecasts on Continuing Urbanisation | Knowledge for policy n.d.). In this scenario of dense built environments with high population density, conventional urban development jeopardizes the presence of green areas and it leads to a reduced resilience and ability to buffer the cities' capacity in dealing with critical events associated to climate change, such as heat waves, abrupt changes in storm patterns, or floods (Gómez-Baggethun and Barton 2013). The recurrence of these extreme events is projected to increase in cities in the next decades, especially in the most vulnerable areas of the world. The Mediterranean region has been identified as one of the most affected by climatic events in the coming decades, where the temperature is expected to increase 2.2 ∘C in 2040, and extreme events, such as droughts or heavy precipitations, are likely to intensify up to 20% in all seasons except for summer (MedECC: Risks associated to climate and environmental changes in the Mediterranean region n.d.). In addition, Mediterranean cities´ aging population, compactness, social inequity, and high population density make them particularly vulnerable to these environmental events (Luterbacher et al. 2006; Paz et al. 2016). Urban environments in this region need to consider immediate solutions to minimize this impact by synthesizing the existing scientific knowledge and providing a systematic framework across disciplines to manage climate change associated risks (Cramer et al. 2018).

In this context, the urban green infrastructure (UGI) management is presented as a suitable nature-based solution (NBS) to adapt urban environments to climate change effects; to address densification in cities; to enhance green space provisioning; and, consequently, to deal with the environmental degradation and social inequity (Escobedo et al. 2019; European Commission 2015; Gill et al. 2007; Maes et al. 2019). The suitability of the UGI is due to the versatility of its elements, which provide a wide range of ecosystem services (ES) at the city and site level, such as air filtration; microclimate regulation; cumulative effect on runoff; groundwater recharge and evapotranspiration; and social, health, and restorative benefits (Baró and Gómez-Baggethun 2017; Demuzere et al. 2014; Millennium Ecosystem Assessment Program 2005). The harnessing of the UGI will be more necessary in Mediterranean medium-sized compact cities (Yiannakou and Salata 2017), where risk and disaster events associated with climate change, the loss of the traditional compact urban model and the process of coastalization will be aggravated (Carinanos et al. 2018; Founda et al. 2019; Mavromatidi, Briche, and Claeys 2018).

The benefits provided by the UGI assets derive from a wide variety of functional and structural elements at different scales, from smaller artificial structures - such as planter boxes, bioswales, green roofs, or green walls - to more extensive areas such as urban forests and other natural areas near the city (European Commission 2013; US EPA, OW 2018). It is worth mentioning that peri-urban areas also contribute to the provision of ES in the urban environment. Urban and peri-urban forests offer every type of ES (regulating, cultural, and provisioning) with relevant impact at local, regional, and global scales (Dobbs et al. 2018). The strategic role these forest areas have should also be highlighted with regards to social interaction and inclusion, economic and cultural exchange (Borelli and Conigliaro 2018) and risk reduction and planning for disaster management in cities (Carinanos et al. 2018). Then, the management of available UGI areas and the provision of new ones not only improves urban environmental quality but also the adaptative and the resilience capacity of the city (Verdú-Vázquez et al. 2017). Moreover, the proximity to UGI elements is closely linked to environmental justice in urban areas. A greater level of green availability decreases the exposure surface to heat waves and waterlogging, while an enhanced accessibility to environmental refugees reduces inequity and strengthens inhabitants' welfare throughout a major provision of green spaces to a wider population, irrespective of their socioeconomic status (Rigolon et al. 2018; Zhu, Ren, and Liu 2019). This is so much so that UGI availability and accessibility are variables of major significance for green equity to be understood as a fair and equitable access to green areas and to the services they provide (Nesbitt, Meitner, Girling, and Sheppard 2019), especially during unexpected episodes of restricted mobility across the city such as the recent Coronavirus Disease 2019 (COVID-19) pandemic (Slater, Christiana, and Gustat 2020).

In fact, some studies conducted in compact Mediterranean cities, whose urban form is typically space-limited (Diappi 2015), have shown how the contribution of every green space - irrespectively of its size - will become even more critical for citizen welfare and for the city adaptative capacity in terms of thermal regulation, air quality improvement, water retention, and energy performance (Battisti et al. 2019; Matos et al. 2019; Pace et al. 2020). Moreover, recent research shows strong evidence on how the number of green areas and the greater access to them have an important role in creating a culture of well-being and in reducing social disparities (Nesbitt, Meitner, Girling, Sheppard, et al. 2019). An increased exposure to green spaces is associated with positive health outcomes (better cognitive function in adults, improved mental health, or lower risk of a number of chronic diseases, among others), social cohesion, and improved urban dwellers´ perception of well-being (Dadvand and Nieuwenhuijsen 2018; Engemann et al. 2019; Enssle and Kabisch 2020; Hong et al. 2019).

Therefore, the framework for UGI identification needs not only a multidisciplinary context that involves different stakeholders, from planners ("green providers") to end users ("green beneficiaries") (Hansen and Pauleit 2014; Ugolini et al. 2018), but also have standardized protocols with a common language that are integrated across disciplines and able to optimize the UGI functionality, accessibility, and availability (Jim 2013; Tobi and Kampen 2018). The current methodologies for green infrastructure identification are mainly based either on geographic information system (GIS) techniques (European Environment Agency 2015; Maes, Paracchini, and Zulian 2011) or on spatial analysis methodology focused on the creation of structures from connectivity among the analyzed areas (Liquete et al. 2015). Pulighe et al. (2016), in their study about literature focused on urban green infrastructure mapping, setting out that there are advanced and sophisticated technical methods to assess and identify the functionality provided by green areas in cities, such as spatially-explicit InVEST, i-Tree Eco models, 3D modelling, or landscape structure models (Pulighe, Fava, and Lupia 2016). Nevertheless, it should be noted that these methods have very high application and interpretation difficulties and they are less manageable or accessible for those specialists who attend more to psycho-social and socioeconomic approaches, such as hedonic aspects, aesthetic appreciation, or well-being variables (Kothencz et al. 2017; Shackleton et al. 2017; Votsis 2017). In the same way, green infrastructure elements are classified using many systems, which mainly respond either to structural criteria, based on land cover type, or functional criteria, based on land use type and spatial configuration of green elements (European Commission 2016; Koc, Osmond, and Peters 2016; Panduro and Veie 2013).

On this basis, the current picture is defined not only by the lack of standardized and manageable frameworks for all the involved stakeholders aimed at promoting the UGI identification in Mediterranean urban environments, but also by the urgent need of compact cities - especially the Mediterranean medium-sized ones - for addressing the adaptation to climate change and inhabitants' welfare improvement through the optimization of the availability and accessibility to more functional green areas. This is the starting point of this study, which aimed at setting an UGI identification process with the capacity to maximize the functional green surface for the enhancement of ecosystem service provisioning at urban and site levels. A manageable protocol was developed and implemented for a wider identification and categorization of green areas to include in the UGI. This protocol set the criteria for the definition and selection of a greater number of available green areas on the basis of their spatial distribution, extension, and capacity to provide ecosystem services and to improve citizens' wellbeing. The city of Granada, as a representative of a medium-sized compact city located in the Mediterranean region (Southern Iberian Peninsula), was taken as a case study (A. P. Russo et al. 2017). It is of note that Granada does not have a well-defined UGI nor an integrated plan for its promotion and management.

2. Materials and Methods

The conceptual approach of the proposed protocol supports the main principles for UGI planning, such as integration, determining the target elements within the infrastructure; connectivity, locating green elements within the urban matrix; multifunctionality, identifying the green elements that improve the adaptative capacity of the city; and social inclusion, enabling identification of those urban areas devoid of green availability (Santos 2016). In practice, the framework combines, on the one hand, the categorization of green urban and peri-urban areas in the UGI by previously defining, selecting, and classifying the target surfaces, and, on the other hand, an initial assessment on the availability and the accessibility of the categorized UGI elements. The resulting categorization responds to green areas' spatial distribution, extension, and capacity to provide ecosystem services in terms of wellbeing reinforcement and resilience to climate change.

2.1. Protocol for Target Areas Definition, Selection, and Classification.

First, to define the elements to be included in the UGI, it is considered the capacity of the target areas to participate in the reinforcement of urban resilience and to mitigate the effects of climate change (Dige et al. 2014). Therefore, areas with specific land uses especially active in terms of improving the benefits for citizens through the provision of ES, such as air quality enhancement, cooling effect in summer, or heat island effect mitigation, are identified (Maes, Paracchini, and Zulian 2011). These land use types are analogous to the land cover classes proposed by the Corine Land Cover Program (CLC) at the third level of geographical application, and at a 1:100,000 scale (Heymann et al. 2000) (Table 1). In order to deal with the most recent information and to acquire spatial data at a finer scale, we made an analogy between CLC classes and land uses referred by the national land cover system (Spanish Land Use and Land Cover Information System - LCIS) for 2013 at a 1:10,000 scale (Spanish National Geographic Institute 2013) (Table 1, Appendix A).

Table 1 also qualitatively summarizes how these land cover types support the provision of ES. Regulating ES ("Reg. ES") considered are local and regional climate, air quality and carbon sequestration, pollination, flood prevention, erosion prevention, and nutrient sequestration. Provisioning ES ("Prov ES") targeted are crops, livestock, fodder, fiber, timber, energy, water, and medicines/biochemicals. Cultural ES ("Cult ES") are recreation and tourism, landscape aesthetics, knowledge systems, cultural heritage, and natural heritage. The qualitative assessment stems from previous research on the relative capacity of different land cover type to deliver ecosystem services (Burkhard et al. 2009; Depellegrin et al. 2016; Graça et al. 2018; Mexia et al. 2018; Vihervaara et al. 2010) and its scale varies from low ("low") to medium ("med") and high ("high").

Second, after we defined target areas, they were selected within the study area according to their location and to the following criteria:

- The selected green areas should correspond to those with land uses listed in Table 1, that is, those public areas that are part of the UGI, showing the capacity to provide ES for climate change adaptation and mitigation.
- The selected public areas, apart from fulfilling the previous criteria, are located within the city administrative boundaries (urban areas) or immediately adjacent to it, in contact with the urban fringe (peri-urban areas). This spatial delineation fits with the approach proposed by the European Environmental Agency in its glossary for urban green infrastructure (European Environment Agency n.d.), and it also fits with other proposals internationally accepted for urban and peri-urban systems, such as the approach followed by the Millennium Ecosystems Assessment Program (Millennium Ecosystem Assessment Program 2005) or by the Food and Agriculture Organization of the United Nations, FAO (Knuth 2005).
- Finally, other areas that meet the two criteria mentioned above that do not appear in any source

of information are manually added to the cartography.

Land Uses with regulating services capacity (Maes, Paracchini, & Zulian, 2011)	Corine Land Cover classes (level 3)		Correspondence with LCIS (2013)		ES provision capacity		
	CLC Code	CLC Description	LCIS Code ranges	General Description	Reg. ES	Prov. ES	Cult. ES
Green urban areas.	141	Green urban areas.	177, 2005, 158	Green urban areas	med	low	high
Land mainly occupied by agriculture, with significant areas of natural vegetation.	243	Land mainly occupied by agriculture, with significant areas of natural vegetation.	410	Heterogeneous cropland	med	high	low
Agro-forestry areas.	244	Agro-forestry areas.					
Broad-leaved forest.	311	Broad-leaved forest.	From 510 to 580	Woodland and forest	high	high	med
Coniferous forest.	312	Coniferous forest.					
Mixed forest.	313	Mixed forest.					
Natural grasslands	321	Natural grasslands	From 611 to 921 (excluding 917)	Grassland and shrub	med	med	med
Moors and heathland.							
Sclerophyllous vegetation.	323	Sclerophyllous vegetation			low	low	low
Transitional woodland-shrub.	324	Transitional woodland-shrub			med	low	med
Beaches, dunes, sands.							

Table 1. Land cover classes included in the urban green infrastructure (UGI) with capacity to provide ecosystem services (ES) in urban environments, and their correspondence with CLC classes (Corine Land Cover) and LCIS classes (Spanish Land Use and Land Cover Information System). Non-existent classes within the study area, such as beaches, dunes, sands, and moors and heathlands, are not included. Relative capacity of the land cover type to provide ES expressed as qualitative measure: Reg. ES = Regulating Ecosystem Services; Prov. ES = Provisioning Ecosystem Services; Cult. ES = Cultural Ecosystem Services.

Two information resources were used in this study: public green areas mapping for regional capitals and municipalities with more than 100,000 inhabitants over 2004 and 2005, at a 1:5000 scale, and LCIS cartographic base, for 2013, at a 1:10,000 scale (Andalusian Environmental Information Network - REDIAM). Cartographic tasks such as map-making, map edition, and spatial data treatment were undertaken with geographic information systems (GIS).

Third and finally, the classification of the selected areas was based on three parameters: spatial distribution, surface, and capacity to improve citizens´ wellbeing through ES provisioning.

Spatial distribution of green elements in the urban and peri-urban landscape is heterogeneous. This configuration is shown as a network composed by non-linear spatial units defined as patches, connected with each other by linear areas defined as edges or links (Ahern 2017; European Comission 2012; Minor and Urban 2007). Patches are classified in core areas (larger patches) or node areas (smaller patches) according to their physical and ecological behavior in terms of their surface and capacity to host biodiversity (Benedict and McMahon 2000; Borelli et al. 2015; Cook 2002) (Figure 1).

In line with the above, green area classification by surface is based on patches and corridors size (Cook 2002) and refined with the proposed classification for Andalusian cities framed in the global action plan for sustainable development Agenda 21 (Rojas et al. 2004). Four types of green areas are identified according to their extension, to which a surface range is assigned accordingly:

- Large-sized areas, with an extension over 100,000 m2, mostly occupied by natural vegetation and forests (natural parks, urban forests, or peri-urban parks).
- Medium-sized areas, with an extension ranging between 10,000 and 100,000 m2, for communal use, where ornamental vegetation predominates (large urban parks, big squares, or vast public gardens).
- Small-sized areas, with an extension under 10,000 m2, corresponding to supplementary areas, with service and leisure purposes (small parks, squares, or other garden areas).
- Linear spaces connecting the areas defined above are included as links. They mainly correspond to pedestrian avenues with roadways in both margins and a high density of green elements.

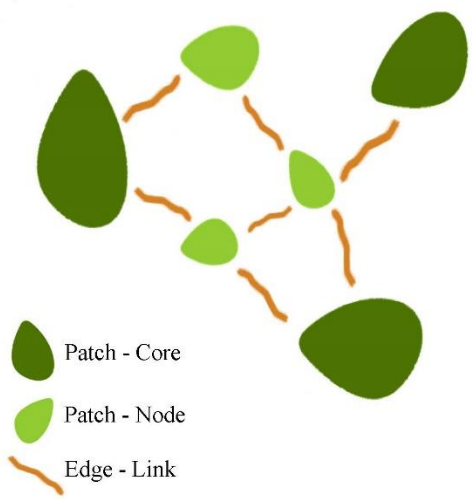


Figure 1. Spatial units identified for green infrastructure in urban environments.

The classification of green areas in terms of their capacity to provide ecosystem services and to improve public welfare relies on the land use type, using the Corine Land Cover classification as a reference. Woodlands and forests are shown to be more active areas due to their higher capacity to regulate local climate; offset carbon from the nearby environment; and face extreme events such as heat waves, erosion, droughts, or floods (Vihervaara et al. 2010). Croplands and urban green areas also contribute to the provision of ES but not as much as the previous land uses (Depellegrin et al. 2016). Transitional woodland/shrub, pastures, or areas with sclerophyllous vegetation are been shown active areas as well with lower capacity to provide ES (Burkhard et al. 2009) (Table 1).

On this basis, and according to the land use matching with the Spanish Land Use and Land Cover Information System (LCIS), we considered the fact that land uses with high ("high") or medium ("med") capacity to provide ES actively contribute to the improvement of welfare conditions for inhabitants. These are green urban areas, heterogeneous croplands, woodland and forests and mixed shrubs and grasslands. Those land uses presenting exclusively "med" or "low" ratings, which belong to LCIS codes 915 (Scattered shrub with grasslands) and 921 (Continuous grasslands), were not considered as active as the rest in terms of ES delivery (Table 1, Appendix A).

After following the processes of definition, selection, and classification, the categorization protocol developed in this study - mainly inspired in Benedict and McMahon's approach of functional hubs and links spread across the landscape (Benedict and McMahon 2000) - defines 4 types of green urban and peri-urban areas (Appendix B):

- Core areas: large-sized areas or patches, that have an extension over 100,000 m2 occupied by land uses with high capacity to provide regulating, provisioning and cultural ES (i.e. natural parks, urban forests, or peri-urban parks).
- Node areas: medium-sized areas (extension range between 10,000 m2 and 100,000 m2) with medium and high capacity to provide ES. As an exception, crowded areas (parks, gardens, or squares), smaller than 10,000 m2 and located within the downtown district or adjacent to it, are categorized as node areas.
- Links: areas with linear spatial distribution connecting core and node areas with each other, such as pedestrian avenues or roadsides with high density of green elements. These edge areas are occupied by land uses with medium and high capacity to provide regulating and cultural ES.
- "Other" areas: this type of areas does not respond to any of the previous classes (cores, nodes or links) mainly due to their low surface. Therefore, areas set as "Other" correspond to every urban public space smaller than 10,000 m2, located out of the downtown district and available to all the population. Their distribution is heterogeneous as they are present throughout the urban fringe and the urban matrix as stepping stones. Abandoned and ruderal spaces, pocket parks, green walls or green roofs, public green spaces in neighborhoods, and green spaces surrounding public and private buildings are defined as "Other" areas (Green Surge 2015). "Other" areas that differ from scattered shrubs with grasslands and continuous grasslands have medium and high capacity to provide ES, especially regulating services, such as local climate regulation, air quality, pollination, or flood and erosion prevention, as well as cultural services, such as recreation, landscape aesthetics, and cultural and natural heritage.

Figure 2 shows the protocol schema followed for the categorization of urban green infrastructure elements.

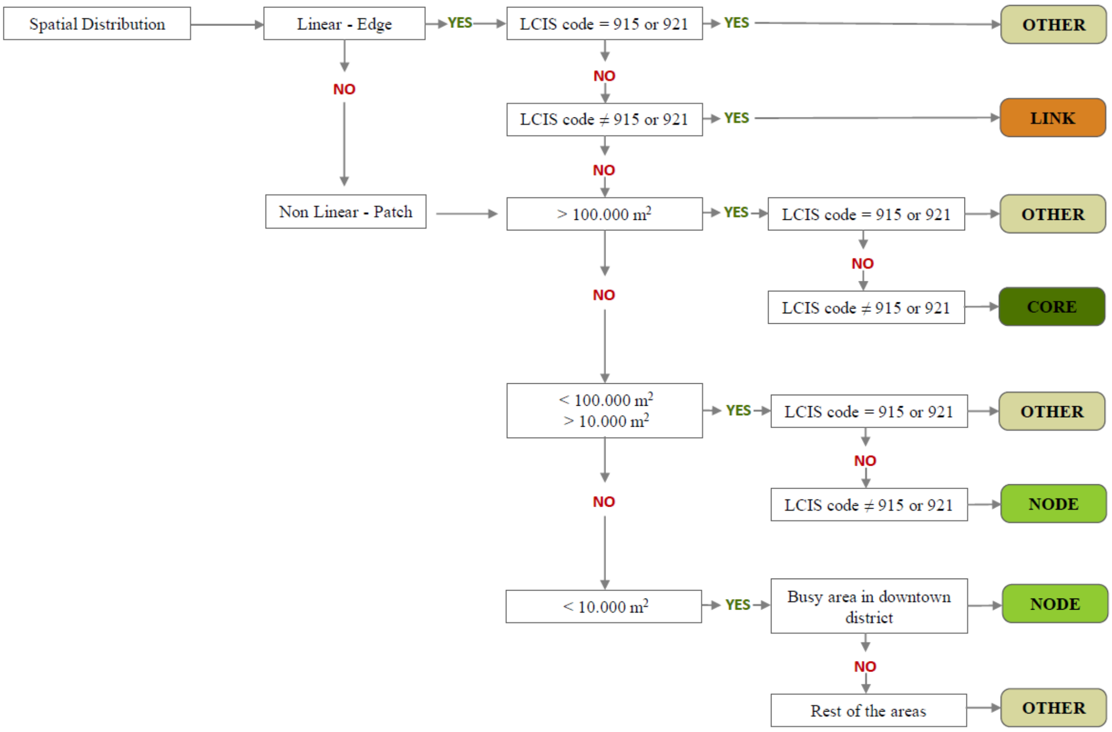


Figure 2. Protocol schema for the categorization of green areas in urban and peri-urban environments, according to their role within the urban green infrastructure.

2.2. Initial assessment of green availability and accessibility.

For an initial assessment of the of the UGI availability and accessibility, we obtained surface and population data from the Municipal Register of inhabitants for 2017 for the 31 neighborhoods of the city (Granada Town Hall Website 2019).

The availability was calculated on the basis of the UGI surface per inhabitant of each neighborhood whilst the accessibility was assessed by calculating the distance as a simple measure from the identified green assets (Halden et al. 2000; Silva et al. 2018). Considering as ideal the level of accessibility when it takes less than 8 min by walking to reach a green area (Rahman and Zhang 2018) and on the basis of the Accessible Natural Greenspace Standards (ANGSs) (Natural England 2010), we set two distance thresholds: 300 m and 500 m to the nearest green space. An additional threshold at 100 m was also set to assess the immediate access to any categorized green area, which is key for vulnerable populations such as the elderly, chronically or mentally ill, disabled citizens, and other minorities. According to these criteria, the percentage of surface within these thresholds is also expressed in relation to the total urban area.

2.3. Description of the case study area.

The City of Granada (37.179937, -3.603489; 680 meters above sea level) is located in the southeast of the Iberian Peninsula, with an extension of 88.9 km2 (reference spatial data of Andalusia - DERA, 2016) (Figure 3a). The study area is representative of a medium-sized compact city in the

Mediterranean region according to the population rank (between 200,000 and 500,000 inhabitants), population density (2657.93 inhabitants/Km2), high contiguity and proximity of dwelling units across districts, the clear separation between urban and rural land use at urban fringe, the existing public transport system spread throughout the town, and the accessibility to most of local services on foot or by public transport (OECD 2012b; Population by region - Urban population by city size - OECD Data n.d.; Spanish Statistical Office n.d.; Spanish Urban Agenda n.d.).

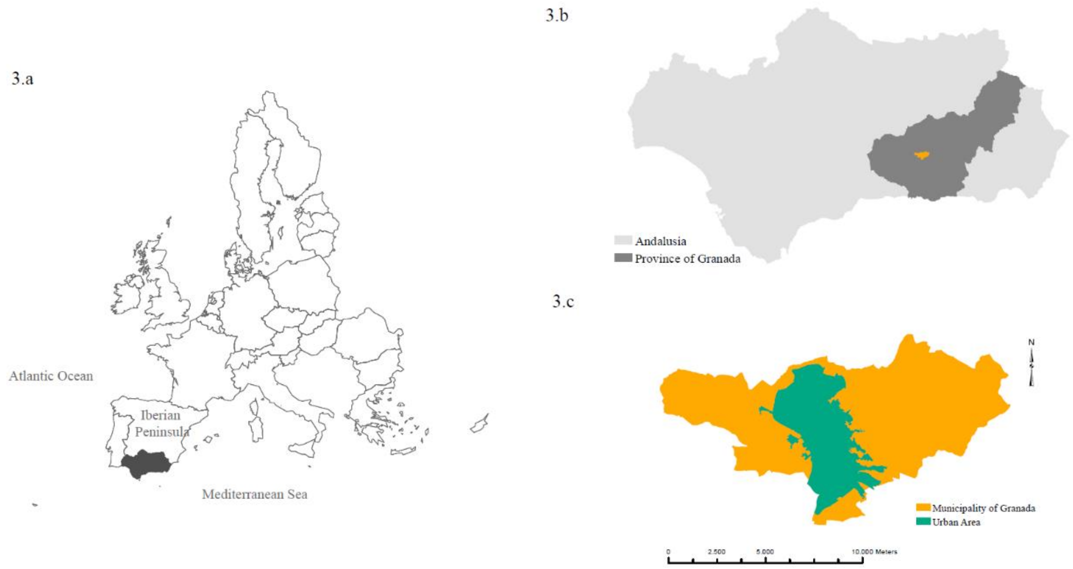


Figure 3. Case study location: (a) Andalusia's and Granada's location within the Iberian Peninsula; (b) Granada's municipality location within the province; (c) Urban and municipal area of Granada.

The city presents a continental Mediterranean climate, with hot, dry summers, and cold winters. The average annual temperature for the 1981–2010 period was 15.6 ∘C, and the average annual rainfall was 359 mm (Spanish Weather Agency - AEMET, 2016). The municipality of Granada (Figure 3b, c) shows a wide thermal amplitude due to its geographical location in a wide depression formed by the Genil River and within the valley of the Sierra Nevada mountain range (Cariñanos, Casares-Porcel, and Quesada-Rubio 2014). The temperature range recorded in Granada for the 1981–2010 period was 14.3 ∘C. The greatest value was recorded during the summer period, when thermal amplitude reached 17.2 ∘C (Spanish Weather Agency - AEMET, 2016). Granada is one of the Mediterranean cities showing a greater frequency of heat and cold waves (Cuadrat, Serrano-Notivoli, and Tejedor 2013; Tomczyk, Półrolniczak, and Bednorz 2017). The records of heat waves occurring in Granada since 1975 show that almost 50% of these extremes have occurred since 2011 (Spanish Weather Agency - AEMET 2018).

It should be also highlighted that Granada is one of the most affected cities in Spain by greenhouse gas pollution and emissions, with 2017 being the year with the worst air quality in the historical data series of the city (Ceballos 2017; European Environment Agency 2017; Ministry of Agriculture and Fisheries 2017; Regional Government of Andalucia 2019). As an indicative value, long-term mortality impact of decreasing ozone and PM2.5 in Granada, expressed as the total annual number of postponed deaths, was set in 61 for the period of 2004–2006 (Pascal et al. 2013).

The current scenario in the city of Granada does not yet have an integrated plan of UGI management. According to the information provided by the Environmental Information Network of Andalusia (REDIAM), Granada's urban area has 363 registered green areas, of which 341 have an extension smaller than 10,000 m2. The remaining 22 green areas have an extension ranging between 10,000 and 100,000 m2. The total surface of public green spaces within the urban area is 1,141,884.7 m2. Considering the population census for 2017, the average value of public green area per inhabitant, in square meters, is 4.9 (Table 2, Figure 4a).

Population (inhabitants)	232,770
Municipality Area (m2)	87,921,138.7
Urban Area (m2)	20,661,438.0
Number of Public Green Areas	363
Number of Large-sized Areas (Surface >= 100.000 m2)	0
Number of Medium-sized Areas (Surface 10.000 - 100.000 m2)	22
Number of Small-sized Areas (Surface < 10.000 m2)	341
Public Green Urban Areas Surface (m2)	1,141,884.7
Public Green Area Surface (m2) / inhabitant	4.9

Table 2. Current scenario: data for public green areas in the city of Granada, 2017.

3. Results

The resulting scenario after implementing the protocol described, shows 443 public green areas identified, which represents a 22.1% increase as compared to the pre-existing data. Among these areas, 5 large-sized areas not considered in the current scenario and 70 medium-sized areas were identified as UGI elements. The number of large and medium-sized areas represents an increase of 100% and 218.2% respectively. Regarding small-sized areas, 368 were recorded within the proposed scenario. A peri-urban forest adjacent to the city boundaries is included so its full extension was completely located within a unique protected area, the Generalife meadow. Nevertheless, the northern zone of the meadow is slightly distant from the city. It should be noted that this protected area represents 50.2% of the whole registered UGI in the proposed scenario (Table 3, Fig. 4.b).

In this context, the total surface of public green spaces in urban and peri-urban areas would come to 7,470,561.3 m2, which means a 554.8% increase if we compare both scenarios. Consequently, the mean public green area per capita would rise to 32.1 m2/inhabitant. Even under a more restrictive approach, excluding the protected area of the Generalife meadow from the proposed scenario due to its distance from the city, the average of public green area per inhabitant would still be higher, coming to 15.9 m2/inhabitant (Table 3 – Fig. 4.b).

3.1. Categorized green areas.

The major contribution to the UGI in terms of number of spatial units relies on the areas defined as "Other," with 374 spaces, mostly (86.1% of them) fully located within the urban area. Land uses in these "Other" areas mainly correspond to parks, squares, and gardens (LCIS 177), although scattered shrub and continuous grasslands (LCIS 915 and 921) were also identified. Regarding green spaces defined as Nodes, there were 49 areas homogeneously distributed within the urban (65.3%) and peri-urban area (34.7%), with most of them being parks, squares, and gardens (Table 4, Fig. 5).

In terms of surface, the 5 core areas identified, which are composed by forests, woodlands, and dense shrub, were the greatest contributors (61.9%) to the whole green area. Four of them are along the urban fringe, and the other one is located within the urban area. Nodes and "Other" areas contribute to the whole registered surface of patches identified within the UGI at 16.9% and 18.5%, respectively (Table 4, Fig. 5).

In addition, 15 linear spatial units defined as links were identified, all of them located within the urban area. These edges contribute least to the whole UGI area, occupying almost 3.0% of the total registered surface in the proposed scenario (Table 4, Figure 5). Those links located in the downtown district include many street trees along them.

In terms of capacity to provide ecosystem services, peri-urban Core areas are presented the highest capacity for regulating, provisioning and cultural ES delivery. Despite Node areas are less active for supporting provisioning ES, they present medium and high capacity for cultural and regulating ES supply, especially for services such as recreation and tourism, cultural and natural diversity, local climate regulation, air quality, pollination, carbon sequestration and flood and erosion prevention. Areas defined as "Other", different from scattered shrubs with grasslands and continuous grasslands, were also found to be active in supporting regulating ES, while their current highest contribution relies on cultural services for recreation, aesthetic appreciation, exercising or cultural and natural heritage.

	Value	Δ
Number of Public Green Areas	443	22.1%
Number of Large-sized Areas (Surface >= 100.000 m2)	5	100.0%
Number of Medium-sized Areas (Surface 10.000 - 100.000 m2)	70	218.2%
Number of Small-sized Areas (Surface < 10.000 m2)	368	7.9%
Public Green Urban Areas Surface (m2)	7,470,561.3 3,722,208.2 (49.8%) + Protected Area= 3,748,353.1 (50.2%)	554.2%
Public Green Urban Areas Surface (m2), excluding protected area	3,722,208.2	
Public Green Area Surface (m2) / inhabitant	32.1	554.2%
Public Green Area Surface (m2) / inhabitant excluding protected area	15.9	226.3%

Table 3. Data for public green spaces in Granada's urban area and increase percentages after protocol implementation.

Type of GI element	Number of areas	%	Urban	%	Peri-urban	%	Surface (m2)	%
Core areas	5	1.1%	1	20.0%	4	80.0%	4,621,460.9	61.9%
Node areas	49	11.1%	32	65.3%	17	34.7%	1,259,340.1	16.9%
"Other" areas	374	84.4%	322	86.1%	52	13.9%	1,381,624.2	18.5%
Links	15	3.4%	15	100.0%	0	0.0%	208,136.1	2.8%
Total	443	100.0%					7,470,561.3	100.0%

Table 4. Public green urban and peri-urban areas classified by type, number of areas, location, and surface.

Figure 4.a. Current scenario

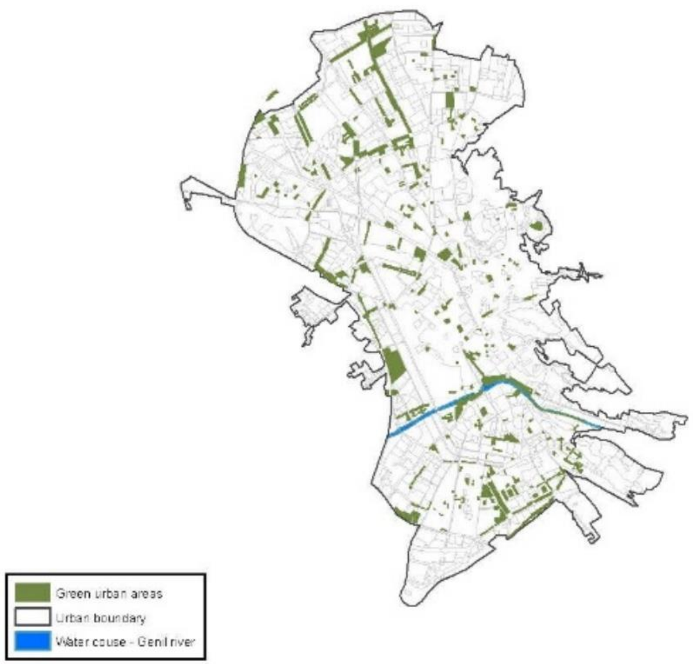


Figure 4.b. Proposed scenario

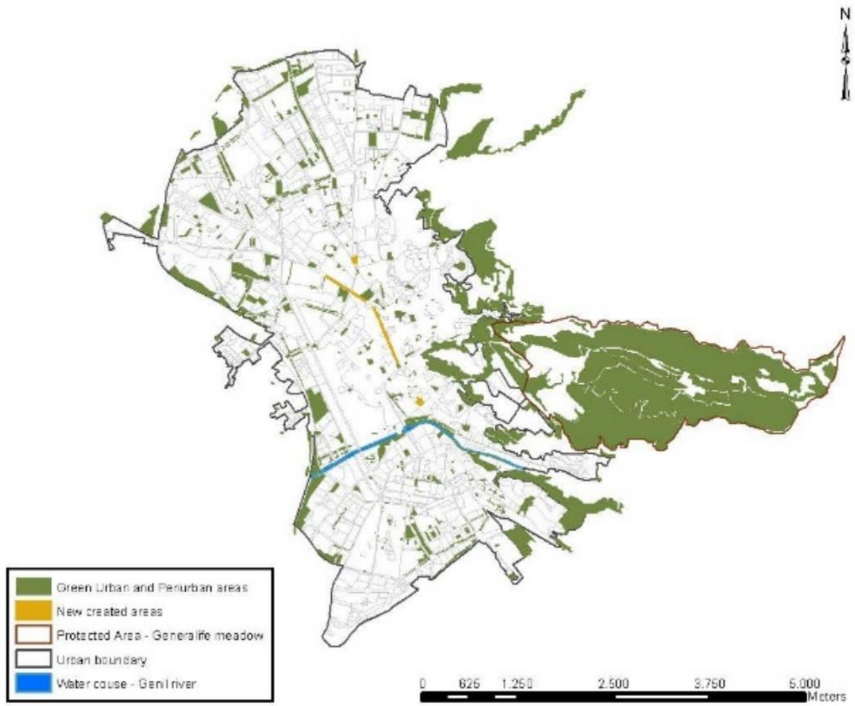


Figure 4. Green spaces in the city of Granada: 4.a. Urban areas identified in the current scenario; 4.b. Urban and peri-urban areas identified after protocol implementation.

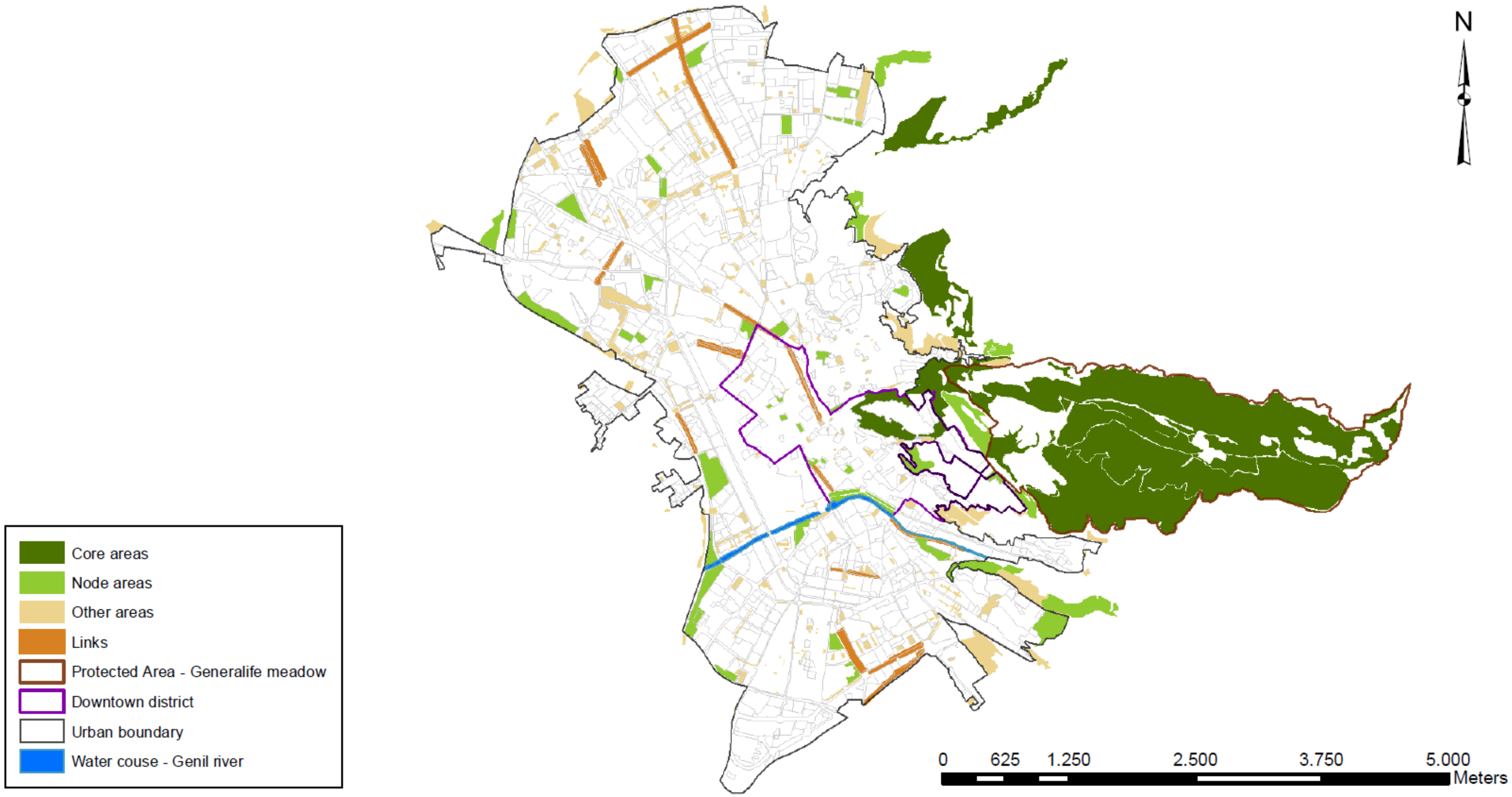


Figure 5. Green urban and peri-urban areas distribution in the proposed scenario, classified by core areas, node areas, "Other" areas, and links. Case study: City of Granada (SE Iberian Peninsula).

3.2 Availability and accessibility.

Results of availability are expressed according to two references: first, the minimum and the ideal green surface per capita recommended by the World Health Organization for urban environments (9.0 and 50 m2/inhabitant) (A. Russo and Cirella 2018). Second, the average calculated for the whole proposed scenario under a more restrictive approach (15.9 m2/inhabitant) and the average calculated for the proposed scenario including the Generalife meadow (32.1 m2/inhabitant) (Table3). The availability assessment shows 16 neighborhoods with less than 9 m2/inh. Two additional neighborhoods are still under the average set for a restrictive scenario whilst five of them have between 16.0 and 32.1 m2 of green space per capita. The remaining neighborhoods have more than 32.1 m2/inh., and five of them exceeded the upper range of 50 m2/inh. (Fig. 6)

Regarding to the accessibility, 67.2% of the total urban area presents immediate access to any of the UGI elements categorized (less than 100 meters). The surface of the city with an UGI element between 100 m. and 300 m. away occupies the 30.5% of the total urban area whilst the 1.5% have an UGI area from 300 m. to 500 m. Almost the 100% of the city presents an ideal level of access to any UGI element, taking less than 8 minutes of walking to reach any categorized area (Fig. 6).

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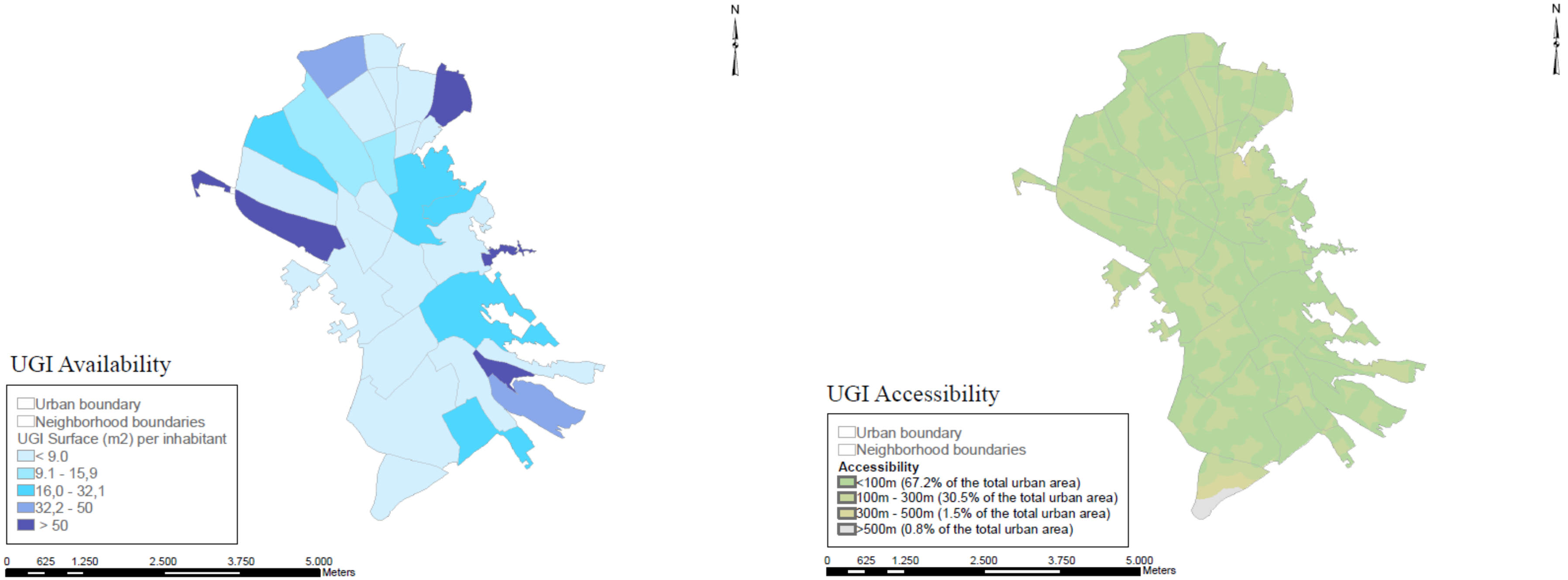


Figure 6. Initial assessment of UGI spatial distribution in terms of availability and accessibility

4. Discussion

New urban spatial designs and the urban green infrastructure still have an unexplored potential for the response to climate and social challenges that cities must face in a near future within the built environment (Andersson et al. 2014). Due to the space limitation characteristic of compact cities, all types of urban green areas with the capacity to participate in the provision of ES should be taken into consideration as they can contribute to climate adaptation, to urban resilience and to social cohesion (Jennings and Bamkole 2019; Stoll et al. 2015), especially in the most vulnerable dense cities such as those in the Mediterranean.

To deal with these challenges, we carried out a process for UGI identification that first combines both quantitative and qualitative concepts. Second, it considers structural and functional variables for areas categorization. Third, it was defined using common language, spatial heterogeneous conditions, and finer local and site scales. The resulting scenario attended to urban and peri-urban green areas spatial distribution, extension, and their capacity to provide ecosystem services. An updated picture of the city was drawn, which better fits with the current functional green network in Granada showing a versatile Urban Green Infrastructure, that is receptive to the implementation of specific plans and measures at district, neighborhood, and site scales.

The application of the defined protocol coped with the compact cities´ densification-associated threats by allowing the identification of a greater number of public urban green areas, typifying existing ones and providing new green spaces on built sites (Haaland and Konijnendijk van den Bosch 2015). Moreover, the consideration of variables such as the characterization of land-use, the accessibility to green spaces or the diversity of active areas in terms of ES provisioning, leads to avoid the complexity for UGI identification (Bartesaghi Koc, Osmond, and Peters 2016). In this sense, the outcome of this methodology would be particularly relevant in the Mediterranean region, where the lack of manageable frameworks across disciplines makes difficult the settlement of the urban green infrastructure as an integrated resource for climate change management in cities (Cramer et al. 2018). Such is the case of Granada, which does not have an agreed-upon and well-defined UGI to be managed yet. This demand is responded to by the followed protocol, which offers a comprehensive way to standardize the categorization of the existing UGI assets (as Core, Node and Link elements) and the provision of new public green spaces to be functional and accessible, mainly corresponding to stepping-stone areas defined as "Other".

After UGI identification following this protocol, the surface of green area per inhabitant has clearly increased. The proposed scenario supports a green area availability of 32.1 m2 per inhabitant when including the Generalife meadow and 15.9 m2 when excluding this protected area (due to its distance from the city) (Table 3). Even under the most restrictive approach, this average noticeably exceeds the calculated average for the current scenario of 4.9 m2.

Nevertheless, our result is more consistent with the average for Granada´s green area provided by the Informed Cities project, a European initiative driven by Local Governments for Sustainability, ICLEI (InformedCities 2012), for 2009. According to this European platform, the whole green infrastructure surface for the municipal area is 7%, while our outcome sets this percentage between 4% and 8%, depending on whether we consider the contribution of the protected area to the proposed scenario or not. The ICLEI average of green area per inhabitant is calculated at 28 m2, which is close to our result, 32.1 m2/inh., under the least restrictive approach.

The average increase obtained after implementing our protocol should not be understood as a reduction of grey infrastructure. In fact, the current intensive urban development, particularly apparent in Mediterranean areas (Hortas-Rico 2014) involves the sacrifice of existing urban green spaces. Especially in Southern EU cities where the average surface of urban green areas is the lowest within the European region (Kabisch et al. 2016). In particular, at a national level, this average is about 12.5 m2/inh. (Xavier Hernández, Carlos Dominguez, Roger Junqueras 2017), and thus the proposed schema is a good first step for the challenge to provide a larger surface of urban green area per inhabitant. This approach is consistent with the results obtained from the availability assessment, since up to 16 neighborhoods can be observed where the average of green surface per inhabitant did not reach the minimum of 9 m2 recommended by the WHO. In contrast, three peripheral neighborhoods far exceeded the average under the least restrictive approach (32.1 m2/inh.) which was due to their low population density.

Apart from the total green surface increase in the proposed scenario, a greater number of green elements to be part of the UGI was identified, which were categorized as core areas, node areas, "Other" areas, and links. In this respect, the set protocol enables a clear and functional categorization for each green area the basis of measurable variables (Taylor and Hochuli 2017) applicable for both smaller and larger urban areas. Moreover, it can be observed that the wider preexisting green areas acquire a major relevance as they were identified as cores and nodes. Our framework underlines the importance of all green areas in terms of ES provision, particularly highlighting the high capacity of core areas to provide regulating, provisioning, and cultural ES. Node areas are also presented as active in terms of capacity for regulating ES supplying and high level of contribution for cultural services. Similar qualitative assessment stems from areas defined as "Other", however the variability of size and land use type make them an interesting target to improve the ES delivery, especially those services related to mitigation of climate change. In addition, the spatial location of these areas is georeferenced, which is also key factor to assess the potential production and distribution of urban ecosystem services (Holt et al. 2015).

The architecture of downtown districts, with small and limited spaces and narrow or cobbled streets, prevents them from having wider range of core and node areas. The East boundary of the city contains the identified core areas while most of the node areas were located within the West boundary. This spatial distribution can lead to a strategical planning aiming to provide continuity between all these green spaces, consolidating a green belt around the urban outskirts. However, the protocol implementation also shows how this continuity potential between green spaces is difficult to glimpse. The identified links scarcely connect relevant green areas (cores and/or nodes) between each other, but they went through and connect areas defined as "Other" within the urban matrix. The initial assessment on accessibility by distance, shows 67.2% of the total urban area presenting immediate access (less than 100 m.) to a green space and 97.7% was less than 300 m. from any UGI element. Almost 100% of the city was found to be 8 minutes' walk or less from any type of green area. Therefore, the spatial dissemination of "Other" areas leads to the fact that almost 100% of the urban area presents affordable levels of accessibility, as a simple measure of distance, to any UGI element both in downtown and peripheral neighborhoods.

The number of "Other" areas was the highest, with 322 spatial units, 86.1% of which are located within the urban area (Table 4, Fig. 5). It should be firstly noted that compact cities in Mediterranean regions are characterized by the archetypal image of density and urban complexity (Muñoz 2003). These cities have followed a monocentric growth model, around a clear and a dense historical center (Rubiera Morollón, González Marroquin, and Pérez Rivero 2016). In these terms, Granada can be considered a typical medium-sized compact city due to its population variables, density and accessibility patterns (OECD 2012a). The urban configuration for a compact city leads to a physical and spatial limitation, especially in the city of Granada, where downtown´s morphological heritage has remained unchanged over time. In the compact city model, the implementation of new green areas among interstitial spaces within the urban matrix is highly limited (Haaland and Konijnendijk van den Bosch 2015). This is where the importance of these "Other" areas, hereunder discussed, comes into play.

To understand these "Other" areas within Mediterranean medium-sized compact cities, we shall have to consider the concept of stepping-stones in cities, as they are shown as small green spaces connecting isolated patches that can be part of an assembled urban matrix (Andersson and Bodin 2009). This situation would support why the areas defined as "Other", which are typically smaller, play a multifunctional and significant role in a complex and dense urban environment, supporting and connecting local biodiversity reserves, increasing the resilience of the urban ecosystem, protecting dwellers against extremes and providing socio-cultural services (Koyanagi et al. 2012; Niemelä et al. 2010). The typology of UGI included in the category of "Other" identified within the study area, mainly correspond to pocket parks and small squares (the so called "plazas" in Spanish). Moreover, the smallest "Other" areas identified within the UGI , even single green elements such as groups of trees placed at intersections of pedestrian routes, create interesting zones both in ecological and in social terms, to facilitate an equitable access to green spaces and improve the habitability and sustainability conditions in the city (Jim 2004, 2013). Actions for "Other" areas reinforcement among existing structures can be considered as a key measure for the enhancement of the spatial cohesion, connectivity and resilience within the urban matrix (Kong et al. 2010). Specially in Mediterranean dense cities such as Granada, which are particularly sensitive to extremes associated with climate change, such as heat waves and torrential rains. The suitability of strategies promoting "Other" areas stems from the combination of their multifunctional role, in terms of regulating ES provisioning (such as cooling effect or improved thermal comfort) and the strategic usability they have to promote a culture of welfare engagement (Hansen et al. 2017; Quatrini et al. 2019). It is also remarkable that, besides the ecological value, "Other" areas could be a useful structural resource to compensate the lack of links for connecting patches as cores and nodes. Their importance for maintaining the UGI connectivity supports that even small green areas in fragmented urban environments can be significantly important for the ES provisioning (Milliken 2018). In this regard, the results for areas defined as "Other" also highlight a range of possibilities to trigger action measures over smaller green areas behaving as connectors and their smart integration into the compact city (Artmann et al. 2019). It can be observed that the absence of connecting linear spaces is more pronounced in the East and West margins of the urban area, where core areas and wider node areas are respectively located. In addition, the identified links are devoid of relevant areas to connect, especially in the downtown district and in north of the urban area (Fig. 5).

On the basis of the proposed protocol results, three strategic lines of action aligned with the principles for UGI planning come into discussion: first, results locate those green areas which need to be managed by specific local measures at site and neighborhood scale, in order to make them more active in terms of ES provisioning and usability. Second, those city sectors requiring more availability of green surface were identified – they were mainly located in the most southern part of the urban area, albeit more availability is demanded at the whole local context. Third, results show at site scale the different thresholds of accessibility to any of the categorized areas; thus, green access disparities can be compensated by the reinforcement of areas defined as "Other". Indeed, due to the limited land resources and the competition between land use in Mediterranean medium-sized compact cities, the management of areas defined as "Other" within the urban matrix would be the first "quick win" for policy makers to enhance an equitable access to functional green areas. They can be considered as stepping stones with additional capacity to behave as refugees and comfort zones redistributed around the town center. Of note, their usability can also offset social disparities and stress situations during unexpected episodes of restricted mobility within the city, across neighborhoods or between dwelling units, such as in the current COVID19 crisis (Cole et al. 2020; Honey-Rosés et al. 2020).

Results discussion also opens the possibility to further applied research in Mediterranean compact cities under ecological and social approaches. On the one hand, this study would allow the quality of the identified areas to be defined through an exhaustive analysis of the vegetation cover, the surface permeability, present structures or plant species and their influence on the closest environmental conditions within the urban area. On the other hand, the results achieved can trigger deeper assessment on the connectivity, green equity and accessibility patterns to green areas within the UGI, taking into consideration specific socioeconomical and architectural variables. Further research can be also addressed on how peri-urban environments interfaces with the UGI, particularly in those non-urbanized areas (such as farmlands and shrubs, located on the periphery of the city). At the end, the ensemble influence of both UGI assets from the urban and peri-urban area and green infrastructure assets from surrounding rural areas can lead to an improvement in the environmental conditions in terms of ES provisioning, from a local to a regional scale (Pérez-Campaña, Abarca-Alvarez, and Talavera-García 2016; La Rosa and Privitera 2013). Finally, additional research should come from the need to improve the accessibility to peri-urban Core areas from high population density urban areas (Fan et al. 2017), as it is currently happening in Granada for inner-city dwellers. At design and planning levels the continuity between peri-urban and urban green areas can be enhanced by specific actions such as creating walking and cycle paths or creating dedicated public transport itineraries (Žlender and Ward Thompson 2017).

It should be taken into consideration that the schema for UGI identification could have some limitations. That means that other classes of land uses, such as rural areas surrounding the city, are not included in the UGI but into an extended green infrastructure beyond the urban boundary. In the case study, these peri-urban rural areas are known as "Vega" of Granada, a region where prevailing land uses are farmlands and crops. This kind of vegetated peri-urban area commonly has different legal instruments for its management, but it complements UGI functionality by contributing to the biodiversity and ecosystem conservation and at the end, to the delivery of ecosystem services in the urban area (Sirakaya, Cliquet, and Harris 2018). In Mediterranean environments, peri-urban rural areas provide additional ES which significantly contribute to human well-being in urban areas (Balzan, Caruana, and Zammit 2018) but it should be also mentioned that this ES supply to Mediterranean compact cities has decreased due to land cover changes during recent years (García-Nieto et al. 2018). Nevertheless, peri-urban areas where the land is occupied by forests have been included in the proposed scenario. These peri-urban forests - followed by urban forests and street trees - are indeed the UGI elements with highest potential for climate change adaptation and welfare improvement in Mediterranean urban environments, as compared to surrounding rural areas with other vegetation types (Marando et al. 2019).

5. Conclusions

This study defines a framework to maximize and categorize the effective surface of the UGI and to initially assess green availability and accessibility patterns in a Mediterranean medium-sized compact city. Results of the proposed scenario are useful for a better assessment of the potential urban resilience to climate change associated extremes, through the spatial distribution of urban functional green spaces. In comparison with the existing scenario, a greater number of green areas have been included into the UGI, mainly attending to the capacity to improve inhabitants´ wellbeing through the provision of ES. Results also show an increase in the surface and number of green elements to consider for enhancement actions and strategic decision-making towards an equitable provision of green areas for dwellers. This is precisely the point where new areas categorized as "Other" play a major role. Despite being mainly smaller elements and apparently less active in terms of ES provisioning, they are distributed throughout the urban matrix reducing the UGI fragmentation and enhancing the usability, the availability, and the accessibility of green spaces. By means of the management and transformation of these "Other" areas into green spaces with higher ecological, cultural, and social value, the capacity of Mediterranean dense cities to deal with environmental extremes and to engage inhabitants with a culture of sustainability and wellbeing, can be gradually increasing.

Finally, further application and research can take place for stakeholders from different disciplines. UGI assets management should integrate ecological and socioeconomical aspects, towards the immediate need to adapt to climate change associated extremes and to enhance social welfare conditions in Mediterranean urban environments.

Author Contributions: Conceptualization: M.D.-C.; methodology: M.D.-C., P.C.; validation: M.D.-C., P.C.; formal analysis: M.D.-C., P.C.; resources: M.D.-C.; writing—original draft preparation: M.D.-C.; writing—review and editing: M.D.-C., P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank the Spanish National Geographic Institute and the Andalusian Environmental Information Network, Junta de Andalucía, for the spatial data and cartographic base provided for case of study.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Appendix A: Detailed correspondence between CLC and LCIS codes

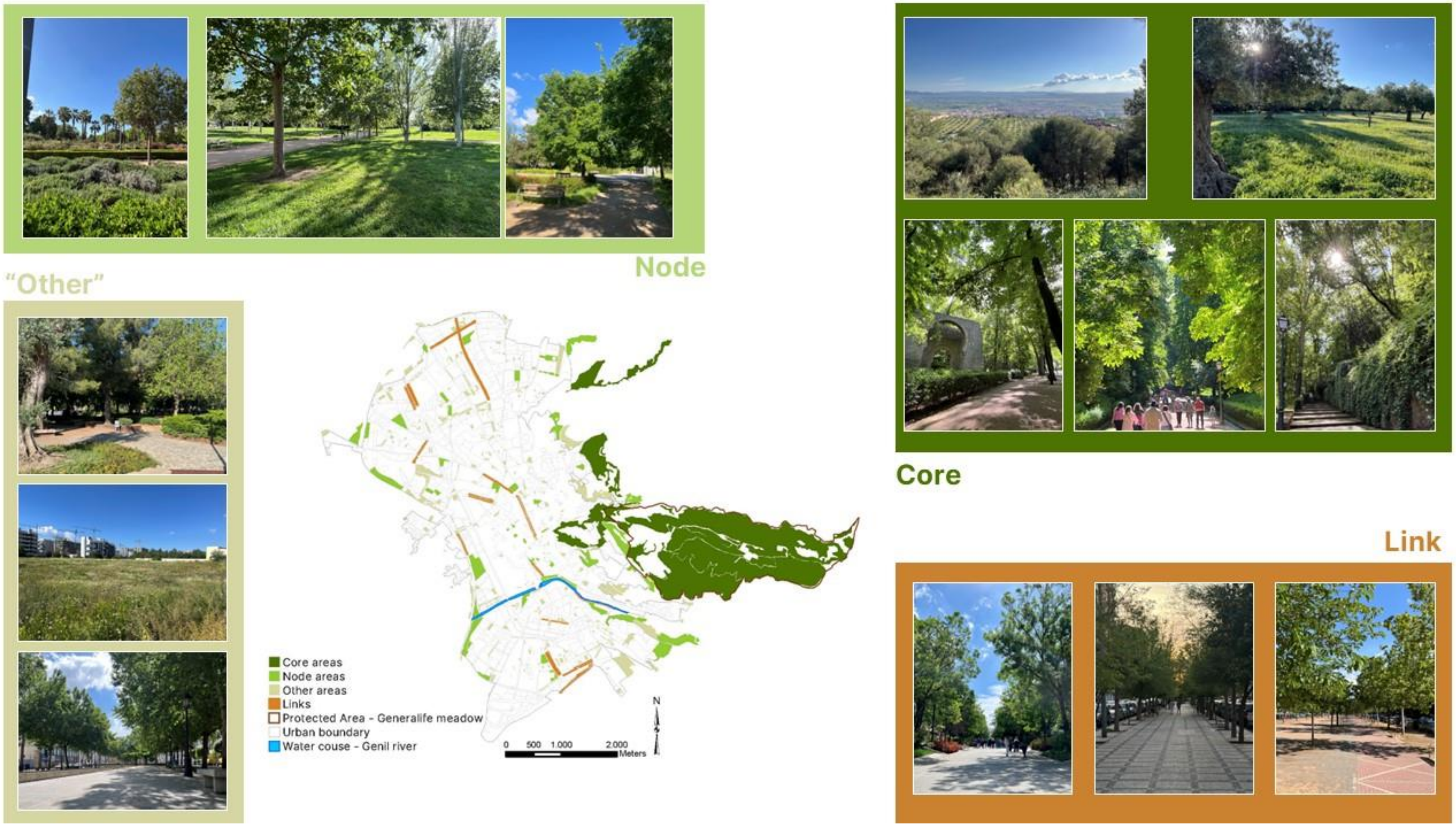
Analogy established between Corine Land Cover (CLC) classes and land uses referred by the National land cover system (Spanish Land Use and Land Cover Information System - LCIS) for 2013.

Land use Source CLC (2012) Level 3	CLC Description	Correspondence with LCIS (2013)	LCIS Description
141	Green urban areas	177	Parks, squares, gardens, promenades
		2005	Landscaped Zones
		158	Playgrounds
243	Land principally occupied by agriculture, with significant areas of natural vegetation	410	Mosaic: Annual crops or grazing land under the wooded cover of forestry species.
244	Agro-forestry areas		
311	Broad-leaved forest	510	Forests: Oak
		530	Forests: Eucalyptus
		540	Forests: Other broad-leaved species
312	Coniferous forest	520	Forests: Conifers
313	Mixed forest	550	Forests: Oak + Conifers
		560	Forests: Oak + Eucalyptus
		570	Forests: Conifers + Eucalyptus
		580	Mixed forests
Scrub and/or herbaceous vegetation associations (all classes within Level 2)		All classes with shrubs, moors and grasslands	
321	Natural grasslands	611	Dense shrub with trees: dense oaks
323	Sclerophyllous vegetation	615	Dense shrub with trees: scattered oaks
324	Transitional woodland-shrub	621	Dense shrub with trees: dense conifers
		625	Dense shrub with trees: scattered conifers
		630	Dense shrub with trees: Eucalyptus
		640	Dense shrub with trees: Other broad-leaved species
		650	Dense shrub with trees: Oak + Conifers

660	Dense shrub with trees: Oak + Eucalyptus
670	Dense shrub with trees: Conifers + Eucalyptus
680	Dense shrub with trees: Mixed tree scpecies
711	Scattered shrub with trees: dense oaks
715	Scattered shrub with trees: scattered oaks
721	Scattered shrub with trees: dense conifers
725	Scattered shrub with trees: scattered conifers
730	Scattered shrub with trees: Eucalyptus
740	Scattered shrub with trees: Mixed tree scpecies
750	Scattered shrub with trees: Oak + Conifers
760	Scattered shrub with trees: Oak + Eucalyptus
770	Scattered shrub with trees: Conifers + Eucalyptus
780	Scattered shrub with trees: Mixed tree scpecies
811	Grasslands with trees: dense oaks
815	Grasslands with trees: scattered oaks
821	Grasslands with trees: dense conifers
825	Grasslands with trees: scattered conifers
830	Grasslands with trees: Eucalyptus
840	Grasslands with trees: Other broad-leaved species
850	Grasslands with trees: Oak + Conifers
860	Grasslands with trees: Oak + Eucalyptus
870	Grasslands with trees: Conifers + Eucalyptus
880	Grasslands with trees: Mixed tree scpecies
891	Arable crops with trees: dense oaks
895	Arable crops with trees: scattered oaks
911	Dense shrub
915	Scattered shrub with grasslands
921	Continuous grasslands

Appendix B

Appendix B: Examples of green urban and peri-urban areas in the proposed scenario, classified by core areas, node areas, "Other" areas, and links. Case study: City of Granada (SE Iberian Peninsula).



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3.2 Capacity of Urban Green Infrastructure spaces to ameliorate heat wave impacts in Mediterranean compact cities: Case study of Granada (South-eastern Spain).

Revista: Land, 2023.

Volumen: 12(5):1076

DOI: https://doi.org/10.3390/land12051076

URL: https://www.mdpi.com/2073-445X/12/5/1076

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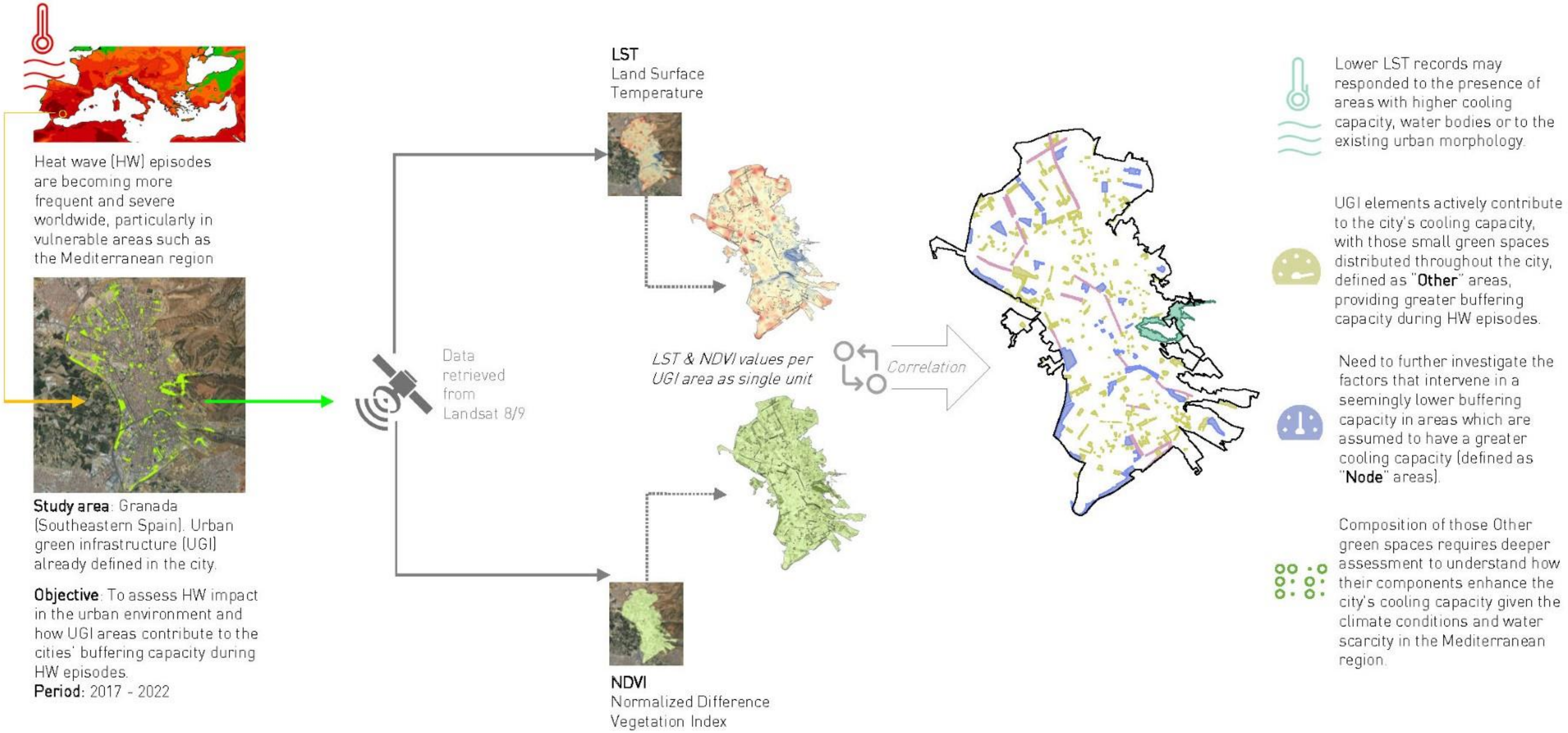
Graphical abstract



Abstract

Heat wave episodes are becoming more frequent and severe worldwide, especially in areas such as the Mediterranean region. This study is aimed at assessing the impact of heat waves in an urban environment and how the areas of urban green infrastructure (UGI) can play a key role in moderating the impacts of these high temperature events. We analyzed Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) data, retrieved from Landsat 8/9 satellite images, during heat wave episodes recorded from 2017 to 2022 in a representative Mediterranean medium-sized compact city. We carried out a correlation analysis between LST and NDVI per area type and as individual units to assess how UGI elements can contribute to the cooling of the urban matrix during heat wave episodes. Those small green spaces distributed throughout the city, defined as "Other" areas, showed stronger negative correlation. These spaces are particularly relevant for Mediterranean cities, where highly limited space in city centers hinders the possibility of having larger surface UGI elements. The study highlights the need for further research on the composition of those small public green spaces to understand how their components enhance the city's cooling capacity given the climate conditions and water scarcity in the Mediterranean region.

1. Introduction

Climate change has increased the frequency and intensity of extreme environmental events in urban and rural areas around the globe (Clarke et al., 2022; Hughes et al., 2018). These extreme episodes have included heat waves, floods, droughts, and cold spells, among others, at a wider spatial scale (World Meteorological Organization, 2022). In particular, heat waves in urban areas worldwide have experienced a significant increase in recurrence and magnitude over the last 20 years of the 20th century and the first decade of the 21st (Almazroui et al., 2021; Dosio Alessandro; Mentaschi Lorenzo; Fischer Erich Markus; Wyser Klaus, 2018).

The impacts of heat waves in cities have been widely evidenced by their negative effects in several ways, such as health impairment, air quality reduction, higher energy demands, and social implications (Santamouris, 2020). A heat wave is commonly described as an extended period of unusually hot weather that lasts for multiple consecutive days and nights and "*indices based on local climatological conditions are used to objectively characterize and declare a heat wave*" ("Homepage | World Meteorological Organization WMO," n.d.). These extreme events have direct effects on inhabitants' health by causing respiratory problems, exacerbating chronic diseases, or increasing heat-related illnesses, mortality, and morbidity (WHO, 2020). Hot spells are also associated with a reduction in urban air quality, triggering higher pollutant concentrations, and consequently leading to health issues (Hou and Wu, 2016; Kalisa et al., 2018; Theoharatos et al., 2010). In addition, events of extreme high temperatures have structural and economic implications in cities since such episodes can lead to power supply problems, higher energy demands in buildings, as well as an increase in cooling costs, while the pedestrian thermal comfort can be harmed at the same time by this consumption requirements (Falasca et al., 2019). Social impacts derived from heat waves are also a significant matter of concern since these episodes make it difficult for people to spend time outdoors, something which directly affects social interactions and citizen welfare (Gasper et al., 2011; McGregor et al., 2007; Salimi and Al-Ghamdi, 2020).

The latest 2022 data presented by the Copernicus Climate Change Service highlights the critical impact of these extreme high temperature episodes throughout the European region, which has suffered the hottest summer on record in 2022, (air temperature 0.4°C above the 2021 average for the months of June, July, and August), with the western Mediterranean (the Iberian Peninsula and parts of France and Italy) being the most affected ("Global Climate Highlights 2022 | Copernicus," n.d.). In addition, the Intergovernmental Panel on Climate Change (IPCC), with high level of reliability, has warned about the urgent need for cities to adapt to these heat waves, which have been primarily increased by human-induced climate change and are projected to be more intense and longer lasting over the short and mid-term throughout the entire continent (IPCC, 2022).

Such scenarios of high temperature episodes will impact European cities across all the region in the near future, with more significant impacts in the distant future (Smid et al., 2019). Central Europe is projected to double the recurrence of warm spells for the period 2020-2049 (Lhotka et al., 2018). The magnitude of heat waves is also expected to increase more for southern-central Europe cities while the largest increase in the number of heat wave days is projected for Mediterranean cities (Guerreiro et al., 2018; Mishra et al., 2015). In fact, the forecast is critical for high temperature climate events along the Mediterranean region in the short-term, where the temperature is expected to increase 2.2 ∘C by 2040 ("MedECC: Risks associated to climate and environmental changes in the Mediterranean region," n.d.). This forecast has been specifically made for the Iberian Peninsula with the present-day conditions used as the reference point. For the mid-term (2046-2065) the estimation foresees heat wave recurrences and durations to increase between 2 and 4 times, whilst for the long-term (2081-2100) the increase ranges from 4 to 40 times more (Pereira et al., 2017).

We have carried out extensive heat wave monitoring and assessment in cities through the analysis of the Land Surface Temperature (LST) which is a suitable indicator at time and spatial scales (Cotlier and Jimenez, 2022; Wei et al., 2022). Apart from field measurements, satellite images were the main source of information to perform this analysis, and Landsat was increasingly used for thermal urban environment assessments due to the precision given in terms of resolution (Lemus-Canovas et al., 2020). Nevertheless, some pitfalls *suggesting that "warm surfaces" result in "high air temperatures"* are present in the literature, especially for Urban Heat Island related studies (Parlow and Bonafoni, 2021). In this study, we considered that LST may act as a good proxy for air temperature at city-scale using the spatial resolution of TIR remote sensing. Although LST and air temperature can present different magnitudes, the relationship between these variables suggests a statistical significance and aligned spatial distribution patterns, so areas of high LST can be co-located with areas of high air temperature (Benali et al., 2012; Coutts et al., 2016; Do Nascimento et al., 2022; Mutiibwa et al., 2015; Zhang et al., 2014).

The LST value retrieval from satellite imagery could highlight that the major contribution to lessen and moderate the impact of heat waves is mainly associated with urban green infrastructure (UGI) assets, such as urban forests, parks, water bodies, leisure spaces with impervious surfaces, or smaller green spaces (i.e. green roofs or pocket parks) (Asadi et al., 2020; Gemitzi et al., 2021; McConnell et al., 2022; Mutani and Todeschi, 2020; Wang et al., 2019). The assessment of those UGI areas in terms of greenness or other type of land cover can be efficiently carried out by the Normalized Difference Vegetation Index (NDVI), which is largely used in vegetation mapping and is expected to be correlated with LST values (Ge et al., 2020; Marando et al., 2019; Qureshi and Rachid, 2022; Spadoni et al., 2020). A negative correlation between NDVI and LST is expected to vary from greener areas (high NDVI values) which potentially strengthen the cooling capacity of the cities during heat waves, to those built-up areas with less capacity to buffer the impact of warm spells (Keeratikasikorn and Bonafoni, 2018; Lemus-Canovas et al., 2020; Liu and Zhang, 2011; Vulova and Kleinschmit, 2019).

Thermal effects of green infrastructure and correlation between LST and NDVI values at various spatial scales are generally assessed from a city to a regional, country, or continental level. In a systematic review carried out by Bartesaghi et al. (2018), the researchers underline how relationships between LST and vegetation coverage are traditionally assessed for large areas or whole cities and regions. That research highlights the type and composition of those specific UGI areas most effective for outdoor thermal comfort during high temperature episodes at local levels (Bartesaghi Koc et al., 2018). Nevertheless, there are studies which give insights at a finer scale within urban environments on LST assessment, using as the extent unit Local Climate Zones, which are defined as "regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale" (Stewart and Oke, 2012). Local Climate Zones are considered as predefined static elements assessed as individual units during high temperature episodes (Ferreira and Duarte, 2019; Unal Cilek and Cilek, 2021). Thus, there would still be a challenge in managing specific UGI elements as single units, so they can fulfill their purpose of being especially effective in mitigating heat stress at a micro scale level for a sustainable and resilient urbanization (Pauleit et al., 2019; Zölch et al., 2016).

In view of the above and given that the climate projections point to the Mediterranean region as a hot spot for heat waves (Ali et al., n.d.), analyzing the role of urban green spaces as buffers against such extreme episodes in the cities of this area becomes even more crucial (Maggiotto et al., 2021). This study, consequently, is aimed at analyzing and assessing how UGI areas, per type and as individual units, performed during heat wave episodes which occurred in the last five years in a typical Mediterranean compact city, throughout LST and NDVI values variation with time and their correlation. Finally, those types of UGI areas with the best potential capacity to buffer the impact of warm spells within the urban matrix are identified.

2. Materials and Methods

2.1. Study area.

For this research, we used as a case study a representative medium-sized compact city (Granada) of the Mediterranean region which contains a defined UGI (Delgado-Capel and Cariñanos, 2020). Granada is located in the southeast of the Iberian Peninsula (37.179937, −3.603489; 680 meters above sea level), and it has a total area of 88.9 km2 with a population density of 2,657.93 inhabitants/Km2 (Figure 1). It presents a Mediterranean-continental climate, with an average annual temperature of 14.0 °C for the period of 1981 – 2018 (Spanish Agency of Meteorology, 2020) and is one of the Spanish cities most impacted by heat waves since 1975, with the highest recurrence of heat waves since 2011 (Cuadrat et al., 2013; Spanish Agency of Meteorology, 2022a; Tomczyk et al., 2017).

The target green areas are located in the urban matrix and belong to the proposed urban green infrastructure (UGI) model proposed by Delgado-Capel and Cariñanos (Delgado-Capel and Cariñanos, 2020). This UGI proposal defines four types of green areas, based on their extension, location, and capacity to provide regulating ecosystem services. "Core" areas are defined as large-sized patches with a high capacity to provide regulating, provisioning, and cultural ecosystem services, such as natural parks or urban forests. "Node" areas are defined as medium-sized patches, such as small forests, dense shrubs or grasslands, parks, gardens, or squares, with medium and high capacities to provide ecosystem services. "Link" areas are those with linear spatial distribution connecting core and node areas with each other. "Other" areas correspond to those smaller public urban green spaces (scattered shrubs with or without grasslands, continuous grasslands, isolated groups of trees, or pocket parks combining vegetated with non-vegetated permeable surfaces), heterogeneously distributed, with both medium and high capacities to provide cultural and – especially – regulating ecosystem services, such as local climate regulation, air quality improvement, and pollination, flood, and erosion prevention.

The pre-existing UGI database has been updated with the latest geospatial vector data provided by the national land cover system (Spanish Land Use and Land Cover Information System - LCIS) for 2016 at a 1:10,000 scale, released on 2021 (Spanish National Geographic Institute, 2021) with ArcGIS 10.6 software. In total, 396 urban green spaces have been identified as target areas (Figure 2). New data has been added using Overlay tool. The Map Algebra tool has been used to estimate LST and NDVI values, and Zonal Statistics tool has been used to export LST and NDVI data to the appropriate format for further statistical analysis.

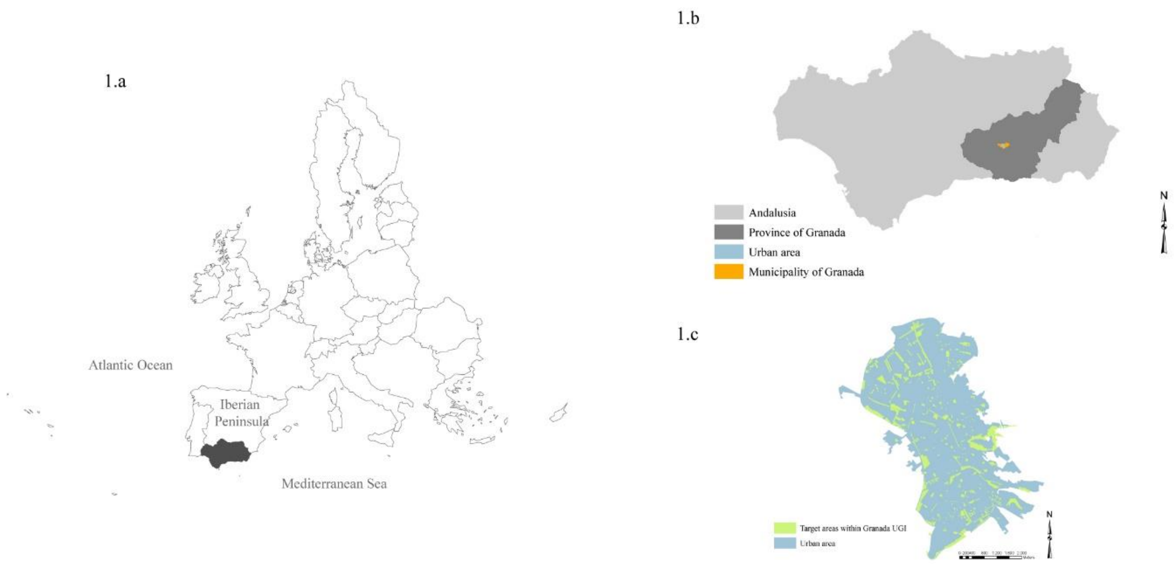


Figure 1. Study area location (1.a) Iberian Peninsula; (1.b) Municipality of Granada within Andalusia region; (1.c) Granada urban area and target areas within the urban green infrastructure (UGI).

2.2. Heat waves identification.

The definition of "heat wave" used in this study is the one given by the Spanish Agency of Meteorology (AEMET), which defines a heat wave as an episode lasting 3 consecutive days or more, in which at least 10% of meteorological stations registered maximum temperatures above the 95th percentile of their series of maximum daily temperatures for the months of July and August from the period 1971 to 2000 (Spanish Agency of Meteorology, 2022b).

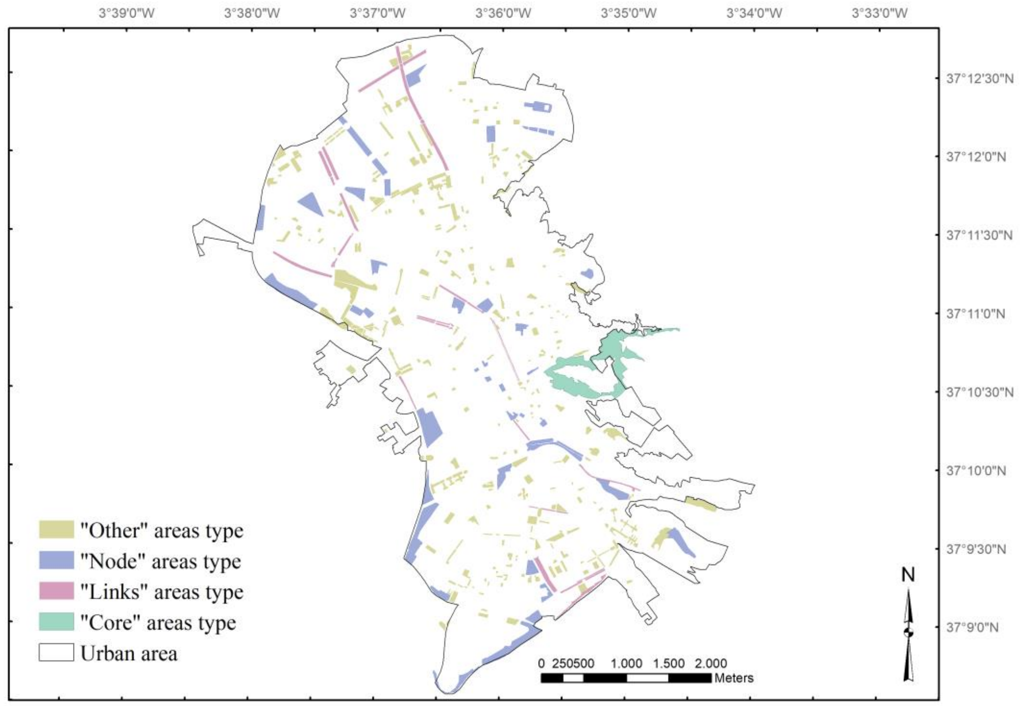


Figure 2. Target areas per type in Granada´s urban green infrastructure (UGI): Percentage of the total UGI area: "Other" areas, 38.59%; "Node" areas 36.84%; "Link" areas, 10.74%; "Core" areas, 13.83%.

2.3. Estimation of Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI).

We carried out NDVI and LST retrieval from Landsat 8 and 9 OLI/TIRS satellite images derived from the U.S. Geological Survey ("USGS.gov | Science for a changing world," n.d.). The suitability of Landsat scenes for this study is mainly due to their temporal resolution (every 16 days), spatial resolution, and the probability of obtaining minimal cloud cover (Grigoraș and Urițescu, 2019; Naserikia et al., 2019; "USGS.gov | Science for a changing world," n.d.)(Table 1). It should be noted that data is only available for daylight hours.

Sensor	Band		Wavelength	Resolution
Operational Land Imager (OLI)	4	Red (R)	0.64 - 0.67 µm	30 m
	5	Near-Infrared (NIR)	0.85 - 0.88 µm	30 m
Thermal Infrared Sensor (TIRS)	10	TIRS 1	10.6 - 11.19 µm	100 m

Table 1. Spectral bands used for NDVI and LST retrieval from Landsat 8 and 9 (OLI/TIRS) images.

NDVI has been calculated from the Landsat 8-9 OLI sensor as a ratio between the red band (R) and near infrared band (NIR) ("Landsat Normalized Difference Vegetation Index | U.S. Geological Survey," n.d.) (Equation 1).

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{R})}{(\mathrm{NIR} + \mathrm{R})} \quad (1)$$

LST has been calculated from TIRS band data by using the following algorithm (Avdan and Jovanovska, 2016; Jiménez-Muñoz et al., 2014; Sheik Mujabar, 2019; Sobrino et al., 2004; Stathopoulou and Cartalis, 2007; Wang et al., 2015) (Equation 2):

$$\mathrm{LST} = \frac{\mathrm{BT}}{\{1 + \left[\left(\frac{\lambda \mathrm{BT}}{\rho}\right) ln\varepsilon_{\lambda}\right]\}} \quad (2)$$

where,

BT = Brightness Temperature,

λ = Wavelength of emitted radiance (Band 10), 10.8 μm.

ρ = h × c/**σ** = 1.4388 × 10−2 mK (h = Planck's constant = 6.626 × 10−34 Js, c = velocity of light = 2.998 × 108 m/s and **σ** = Boltzmann constant = 1.38 × 10−23 J/K).

ε_λ = land surface emissivity.

In order to retrieve the LST values per the algorithm presented in Equation 2, the first step is to calculate the Brightness Temperature (BT), adjusted to degrees Celsius, by converting the top of atmosphere spectral radiance (U.S. Geological Survey, 2019) (Equation 3):

$$\mathrm{BT} = \frac{K_2}{ln[(K_1/L_\lambda) + 1]} - 273.15 \quad (3)$$

where,

K1, K2: Thermal constants from the Landsat 8-9 file metadata.

L_λ: Spectral radiance, calculated from the Band 10 image re-scaled by its specific multiplicative, additive, and correction factors (Watts/[m^2 * srad * μm]).

Second, the land surface emissivity (**ε_λ**) is determined by previously calculating the proportion of vegetation (Pv) from NDVI values (Sobrino et al., 2004) (Equation 4):

$$P_v = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2 \quad (4)$$

Finally, land surface emissivity (**ελ**) was retrieved by means of the NDVI threshold method (Sobrino et al., 2008), which has been proven to be the most accurate and best performer across methods for LST retrieval from all Landsat missions (Sekertekin and Bonafoni, 2020) (Equation 5).

$$\varepsilon\lambda = \begin{cases} \varepsilon\lambda, \quad NDVI > NDVIs, \\ \varepsilon v\lambda Pv + \varepsilon s\lambda(1 - Pv) + C, \quad NDVIs \leq NDVI \leq NDVIv, \\ \varepsilon s\lambda + C, \quad NDVI > NDVIv \end{cases} \quad (5)$$

The NDVI values range from -1.0 to +1.0, where bare soil surfaces, water bodies, or snow usually show values below 0.1; areas with sparse vegetation may present values between approximately 0.2 and 0.5; and values above 0.6 mainly correspond to dense vegetation ("NDVI, the Foundation for Remote Sensing Phenology | U.S. Geological Survey," n.d.). In Equation 5, **εsλ** is the soil emissivity (0.966) and **εvλ** is the vegetation emissivity (0.973), NDVIs is set to 0.2 and NDVIv is set to 0.5 to cope with global conditions, and C includes natural surface roughness and internal reflections (Jiménez-Muñoz et al., 2014; Sobrino et al., 2004; Wang et al., 2015). Land surface emissivity (**ελ**) takes the value of soil emissivity (εs**λ**, 0.966) when the NDVI pixel score is lower than 0.2 (NDVIs) whilst **ελ** takes the value of vegetation emissivity (εv**λ**, 0.973) when the NDVI pixel score is higher than 0.5 (NDVIv). When the NDVI pixel score is between 0.2 and 0.5, the **ελ** values depend on the proportion of vegetation (Pv) and C, which is defined by the expression **εvλ**Pv + **εsλ**(1-Pv) +C.

In terms of validation, the accuracy of the estimations given by Landsat satellite images for calculating both NDVI and LST (using Operational Land Imager (OLI) Bands 4 (red) and 5 (near-infrared) for NDVI and using Thermal Infrared Sensor (TIRS) Band 10 for the LST input) show no errors with representative magnitudes and are reasonable for the targeted areas (Cook et al., 2014; Jiménez-Muñoz et al., 2014). In addition, calculations with wavelength ranges and different spectral responses for emissivity of vegetation, water, and soil confirm that the proposed method is effective for the retrieval of LST from Landsat 8 and 9 (Tan et al., n.d.; Yu et al., 2014).

2.4. Statistical analysis.

We analyzed LST and NDVI data with MATLAB R2020b software. The mean average, maximum, and minimum values were calculated for each heat wave episode and for each type of UGI area. Since there is only one record for Core area type within the urban boundary, it was excluded from the calculations. Therefore, from the total of 397 target areas under scope, the statistical analysis was carried out against 396 of them (Node, Link and "Other" types).

We assessed the sample distribution with the Kolmogorov-Smirnov test for both variables, LST and NDVI, in all episodes and per event as well (Appendix A). For all cases, the test of normality pointed to a non-parametric distribution. Accordingly, we calculated the Spearman coefficient correlation ($p < 0.05$) between LST and NDVI retrieved values in all episodes, for separated events, and for each type of UGI area (excluding Core type since there is only one record within the urban boundary).

3. Results

3.1. Retrieved information for heat wave episodes.

Based on the heat wave definition adopted by the Spanish Agency of Meteorology (AEMET), and the historical records available (Spanish Agency of Meteorology, 2022a), Table 2 shows the heat waves registered in Granada since 2017, when the proposed UGI by Delgado-Capel and Cariñanos was originally mapped (Delgado-Capel and Cariñanos, 2020). The shortest episode was HW #3, which lasted only 3 days, while the longest was HW #12, lasting almost 3 weeks (18 days). The remaining recorded episodes lasted between 5 and 9 days.

On this basis, scenes were collected from Landsat 8-9. From the 12 episodes registered, 9 scenes were available without cloud cover above the urban matrix and with the same acquisition date (or near enough) to the one when each heat wave was registered by AEMET since 2017. All data was obtained during daylight hours, so calculations from nighttime hours were not included in this study (Table 3).

Year	HW Episode	Start - End dates	Duration
2017	HW #1	13/06/2017-21/06/2017	9 days
2017	HW #2	12/07/2017-16/07/2017	5 days
2017	HW #3	28/07/2017-30/07/2017	3 days
2017	HW #4	02/08/2017-06/08/2017	5 days
2018	HW #5	31/07/2018-07/08/2018	8 days
2019	HW #6	26/06/2019-01/07/2019	6 days
2019	HW #7	20/07/2019-25/07/2019	6 days
2020	HW #8	25/07/2020-02/08/2020	9 days
2020	HW #9	06/08/2020-10/08/2020	5 days
2021	HW #10	11/8/2021-16/8/2021	6 days
2022	HW #11	12/06/2022-18/06/2022	7 days
2022	HW #12	09/07/2022-26/07/2022	18 days

Table 2. Heat Wave (HW) episodes in the city of Granada for the period 2017-2022.

HW Episode	Data source	Date acquired	Scene center time (GMT+1)
HW #1	Landsat 8 (OLI/TIRS)	19/06/2017	11:49:55
HW #2	Landsat 8 (OLI/TIRS)	Not available on required dates	
HW #3	Landsat 8 (OLI/TIRS)	Not available on required dates	
HW #4	Landsat 8 (OLI/TIRS)	Cloud cover above the urban matrix	
HW #5	Landsat 8 (OLI/TIRS)	09/08/2018	11:49:50
HW #6	Landsat 8 (OLI/TIRS)	25/06/2019	11:50:04
HW #7	Landsat 8 (OLI/TIRS)	18/07/2019	11:56:19
HW #8	Landsat 8 (OLI/TIRS)	29/07/2020	11:50:08
HW #9	Landsat 8 (OLI/TIRS)	05/08/2020	11:56:20
HW #10	Landsat 8 (OLI/TIRS)	17/08/2021	11:50:21
HW #11	Landsat 9 (OLI/TIRS)	09/06/2022	11:49:43
HW #12	Landsat 8 (OLI/TIRS)	19/07/2022	11:50:28

Table 3. Landsat 8 and 9 (OLI/TIRS) scenes collected since 2017 from USGS. Worldwide Reference System (WRS): path 200/201, row 034.

3.2. Land Surface Temperature (LST) analysis

Results from the LST estimation (Equation 2) show values for the whole urban area between 48.86 ºC as the maximum temperature and 24.80ºC as the minimum temperature. The warmest episode was the first one which occurred in June 2020 (HW #8) whilst the event with the lowest LST values was recorded one year before, in July 2019 (HW #7). The value range comes from the LST estimation for the whole urban area, so data retrieval covers not only the target areas but also the entire extension of the urban fabric, allowing for a visual pre-assessment of the whole city (Figure 3).

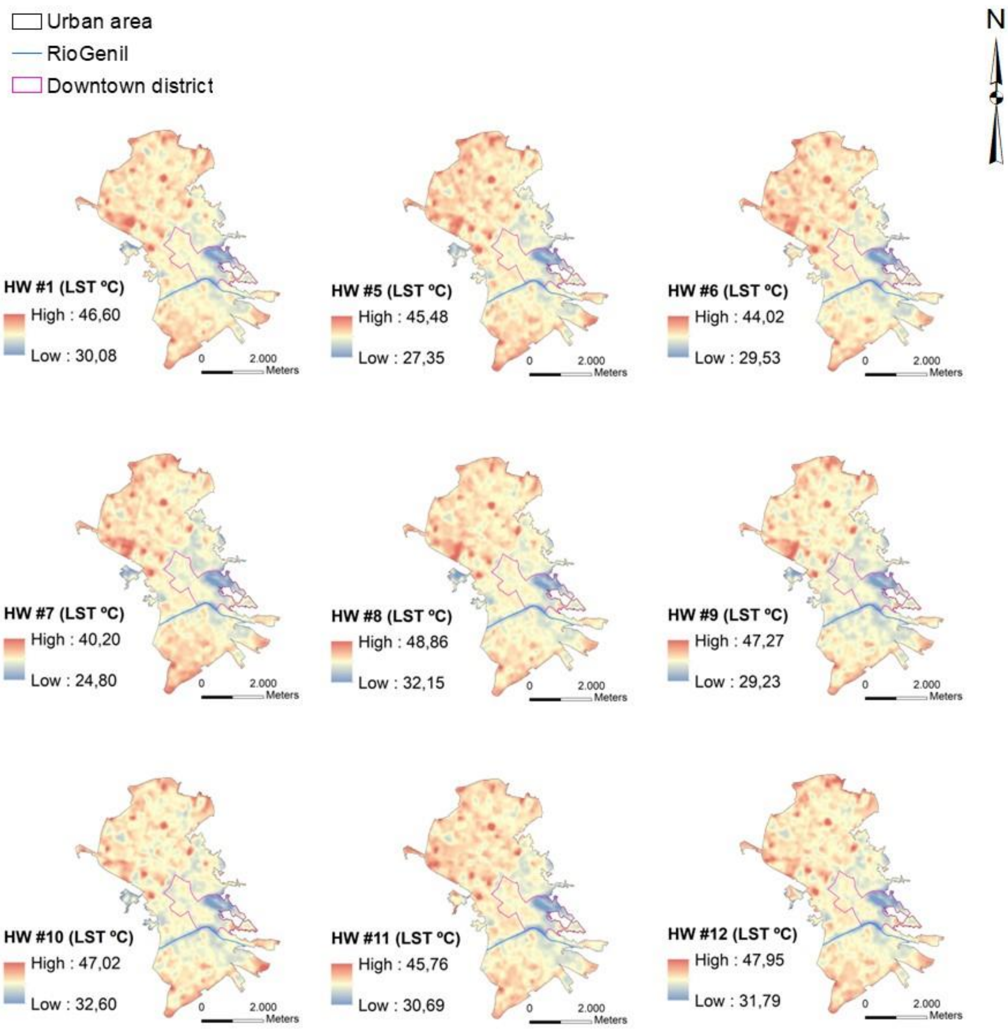


Figure 3. Estimated Land Surface Temperature (LST) over the urban area of Granada. Data acquired on dates within heat wave episodes which occurred from 2017 to 2022.

Figure 4 shows LST values calculated over the targeted UGI areas in Granada. Averages of the mean, maximum, and minimum LST values were calculated for all the areas in each heat wave episode. LST estimation refers to HW #7 as the least extreme, with averages from 32.03ºC to 32.65ºC over the target UGI areas. The first warm spell event registered in 2020 (HW #8) was the most impactful one from all the period under consideration, with temperature averages between 40.55ºC and 41.23ºC. The second half of the period under consideration (years 2020, 2021, and 2022) shows slightly higher LST values than the first episodes for years 2017, 2018, and 2019 (Figure 4).

Results of LST estimation per UGI area type show the higher average values for Link type areas, which are slightly above the values for Node type areas. The lowest LST average values are registered for those UGI areas defined as "Other". Variations of LST values over time respond to the same trend for all area types under consideration. From all the episodes, the event with less intensity occurred in July 2019 (HW #7) for all area types and the most severe one took place in July 2020 (HW #8) (Figure 5a). By looking at the LST estimation per area type for all episodes, the minimum and mean averages present the lowest values in Node areas (36.96 and 37.95, respectively). The highest records of mean and maximum temperature average (38.03ºC and 38.94ºC) are registered for Link type areas. "Other" area types show the highest average of minimum temperatures (37.46ºC), but also shows the lowest average on maximum temperatures (37.81ºC), grouping all the events (Figure 5b). Appendix B shows same averages from NDVI values, which do not differ from one type of area to another, and it can be observed that they are not statistically dissimilar.

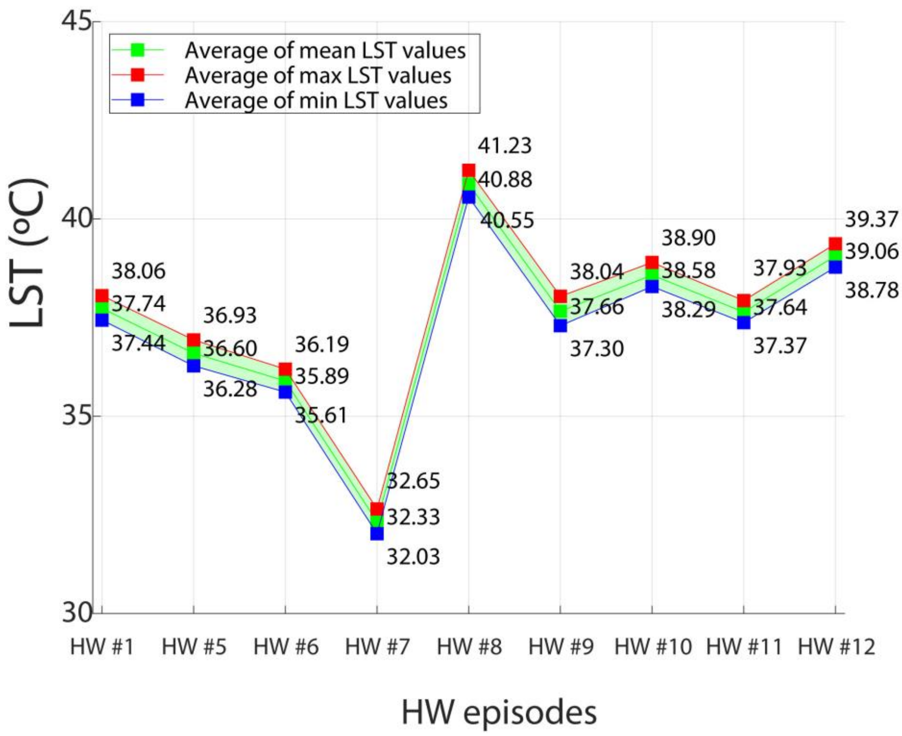


Figure 4. Averages on mean, maximum and minimum Land Surface Temperature (LST) values over the target areas of Granada´s UGI. Data acquired on dates within Heat Wave episodes occurred from 2017 to 2022.

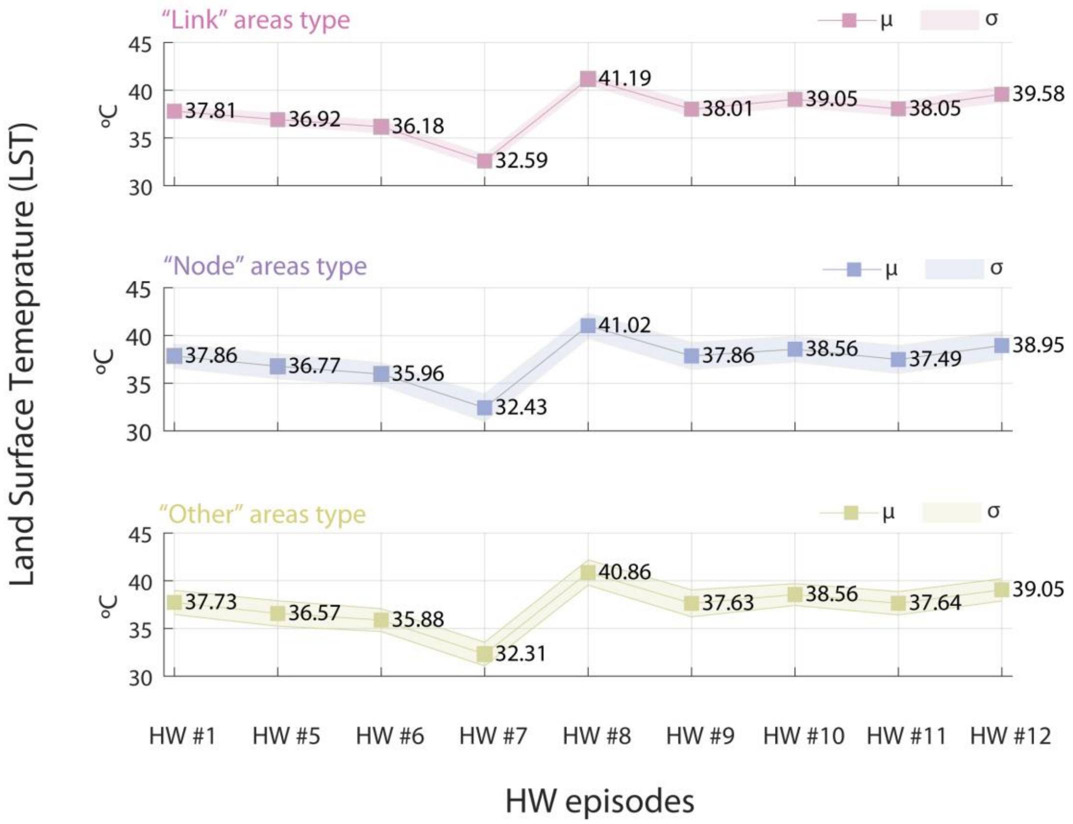


Figure 5. a.- LST mean value per episode and area type.

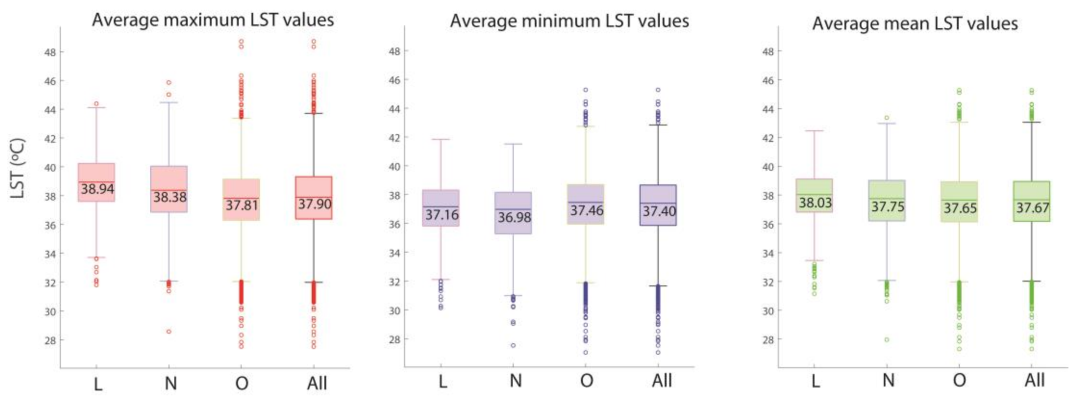


Figure 5. b. LST mean value per are type in all periods. Whiskers determine the extent of the data inliers. Circles represent outliers.

3.3. Statistic correlation of NDVI and LST values

Figure 6 presents the results of the statistical analysis performed on the nine episode dataset, one per heat wave event with available data. The Spearman correlation coefficient between NDVI and LST estimation is shown as statistically significant for all periods ($p<0.01$). Negative correlation coefficients are presented for all periods, with HW #1 (ρ = -0.29), HW #5 (ρ = -0.29), HW #7 (ρ = -0.31) and HW #8 (ρ = -0.26) having the strongest correlations. Compared to those, a moderate negative correlation is observed for episodes HW #6 (ρ = -0.24), HW #9 (ρ = -0.20), HW #11 (ρ = -0.23), and HW #12 (ρ = -0.23) while the weakest correlation appears for event HW #10 (ρ = -0.15). The Spearman correlation analysis between NDVI and LST values per area type for all episodes presents the most negative correlation for the "Other" area type (ρ = -0.27). From the same assessment, a weaker correlation is observed for Link (ρ = -0.04) and Node (ρ = -0.06) area types (Figure 6).

To perform a more granular assessment, we calculated correlations for each type of area per heat wave episode. For all events, the most negative correlation refers to the "Other" area type which was stronger during warm spells HW #1, HW #5, and HW #7, and slightly less negative for events HW #6, HW #8, HW #11, and HW #12. A weaker negative correlation, compared to the one associated with the "Other" area type, can be observed for Node areas during the first episodes under consideration (years 2017, 2018, and 2019). However, NDVI and LST are positively correlated for this UGI area type in the event HW #11. The Spearman coefficient does not show either negative correlation for Link areas for the last 4 episodes registered (Figure 7).

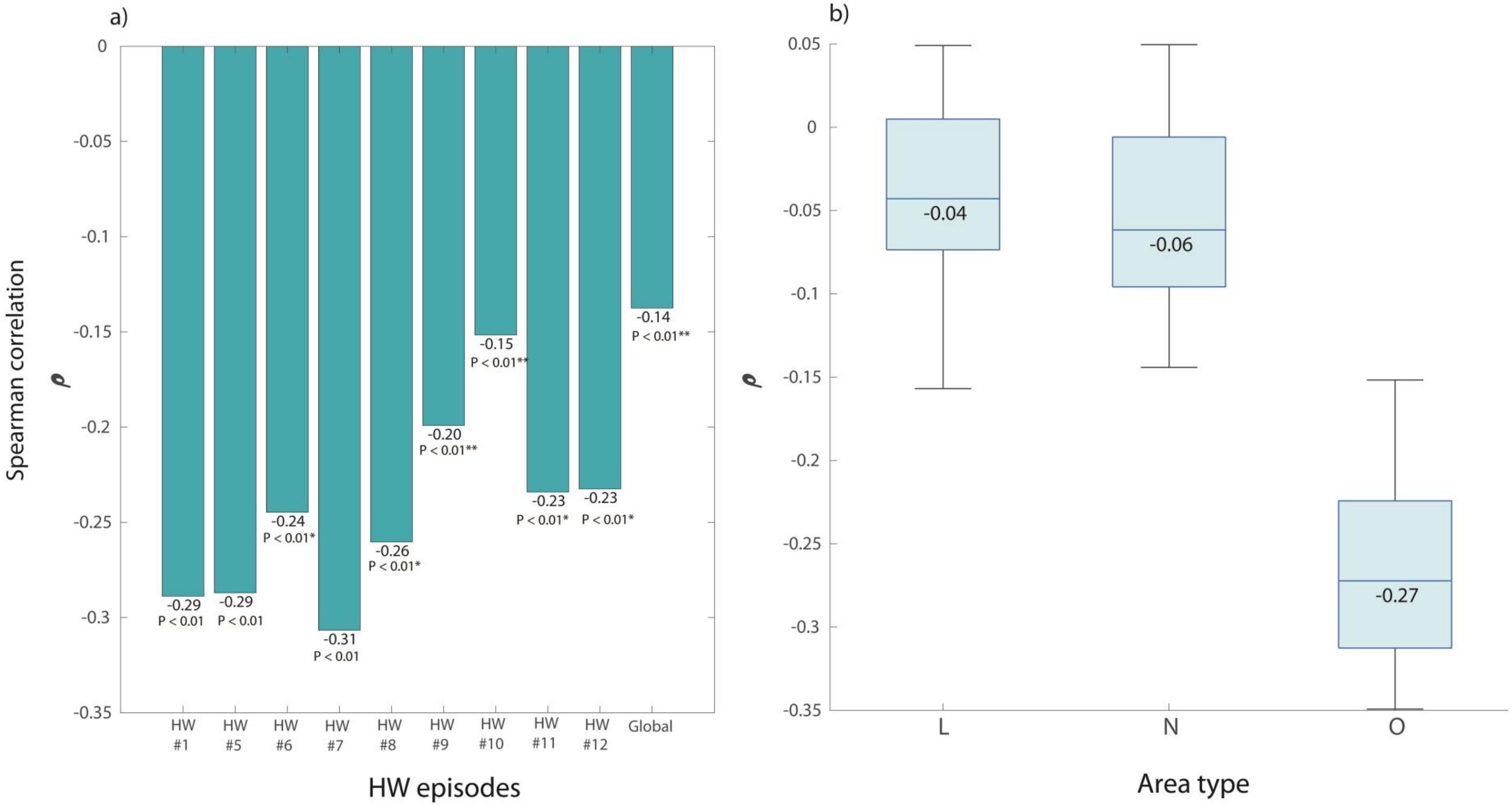


Figure 6. Spearman correlation coefficient between NDVI and LST for all targeted areas per HW episode (a) and per area type for all episodes (b).

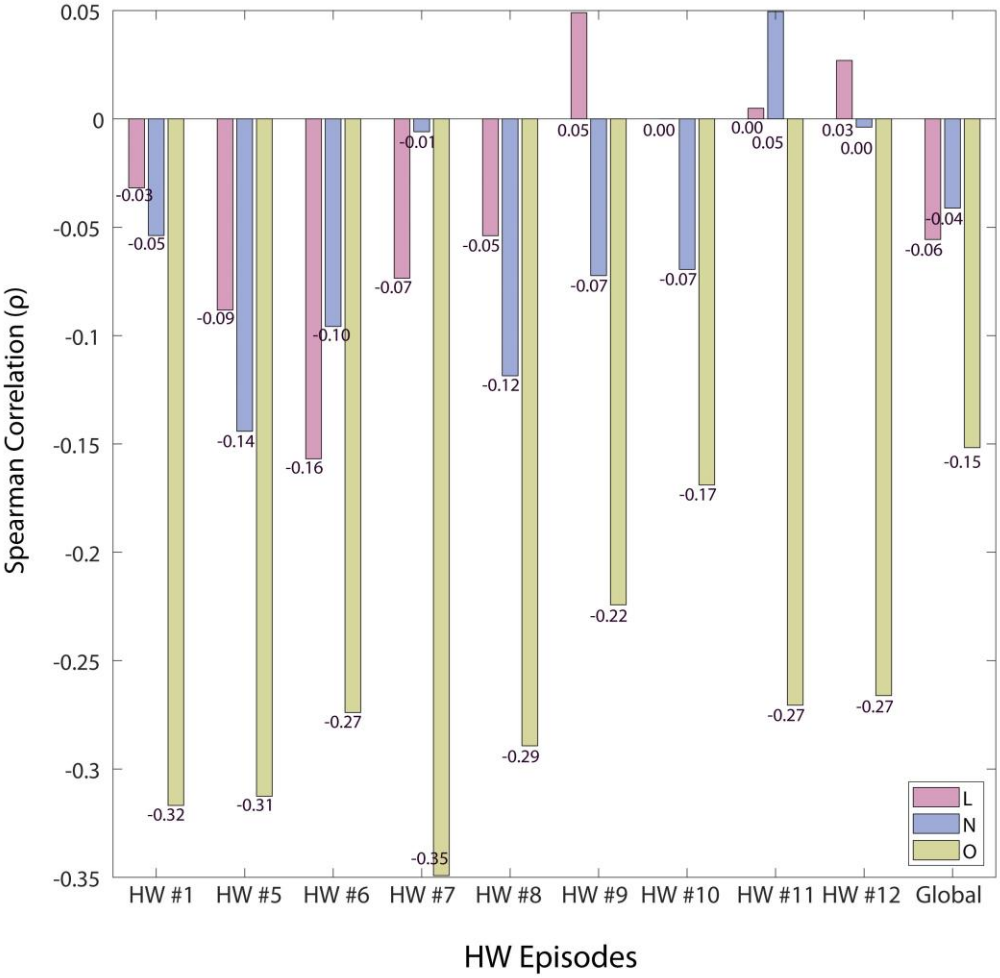


Figure 7. Spearman correlation (ρ) between NDVI and LST per UGI are type for each heat wave (HW) episode.

4. Discussion

Heat wave episodes have significantly impacted the Mediterranean region over the last 3 years and the higher recurrence of these extreme weather events could lead to an increase in pollutant concentration and heat-related mortality and morbidity, among other impacts (Hidalgo García et al., 2022; Luterbacher et al., 2006; Rodríguez-Gómez et al., 2022). In this study we conducted an assessment on the LST values in the urban core of a typical Mediterranean medium-sized compact city during heat wave episodes between the years 2017 and 2022. Rather than covering the entire urban area as a whole like in similar research, the analysis we carried out focuses on the UGI spaces as individual units and area types that, presumably, can provide a better picture of the buffering capacity against high temperatures during hot spell episodes.

The LST values in our study area for the considered period are consistent with similar research carried out in Granada over the 1985 – 2020 period where mean, maximum, and minimum LST values have registered a steady increase of 2.2ºC (Hidalgo-García and Arco-Díaz, 2022). Surface temperature averages over the target areas matches the generalized analysis for the entire urban area over time, with episode HW #7 being the least hot and episode HW #2 registering the highest LST values. The evolution of LST per area type reflects the same trend, with the "Other" area type registering the lowest mean records per period (Figure 5.a) The lowest average of minimum LST values is presented for the Node area type, which would be expected given its capacity to provide regulating ecosystem services compared to the categories Link and "Other". The highest averages are registered for the Link area type, which would be expected given the variety of structural elements different from green areas along its characteristic linear distribution, such as asphalt, sidewalks, and other grey areas devoid of vegetation along an avenue or walkway. Unexpectedly, the "Other" area type, which correspond to these smaller green spaces distributed across all urban matrices, showed the lowest average of the maximum LST values. However, the LST mean value per are type in all periods is not statistically dissimilar (Figure 5.b). Whilst the NDVI average values do not significantly differ between areas type, we could observe an expected high dispersion for type "Other", probably due to the diversity of non-vegetated elements composing these spaces (Appendix B).

The statistical analysis of all the target areas shows a negative correlation between NDVI and LST values in each of the heat wave events recorded from 2017 to 2022. The Spearman coefficient for all areas per episode is statistically significant ($P < 0.01$), presenting higher correlations for the first 5 episodes, until the warmest event in 2020, and getting weaker for the last 4 episodes (Figure 6.a). This variation over time could be potentially related to an increase in the heterogeneity of the areas´ surface under scope (Guha and Govil, 2020). Results on the same correlation analysis between LST and NDVI for all episodes, combined by area type, show higher negative correlations for the "Other" area type than for the Node and Link areas (Figure 6.b). An expected negative correlation is observed in the Node area type per episode, being moderate in all cases except for the last two episodes in 2022. No correlation was found for the Link area type in episodes HW #10 and HW #11 and NDVI and LST were positively correlated for episodes HW #9 and HW #12 (Figure 7). This unexpected behavior would be more prone to occur in all types of UGI areas in southern cities of the European region and could be due to an increase in water stress or water soil scarcity during heat waves episodes, which would reduce or even reverse the cooling effect of green spaces as a consequence of the evapotranspiration reduction (Ward et al., 2016).

Results for the "Other" area type are consistent with the expected pattern of behavior, showing a negative correlation between LST and NDVI in all cases. In line with the observed global trend of recorded temperatures (Figures 4, 5.a), the least hot episodes show a stronger correlation, and hence a better cooling performance (until HW #8), whilst the relationship between NDVI and LST weakens for the final events (from HW #9 onwards) which correspond to the warmest spells (Figure 7). Whilst the stronger relationship between NDVI and LST would be expected for those greener spaces, such as Node areas (based on their definition), the resulting correlation was more negative for "Other" areas type. These results would point to this type of UGI area, which combines vegetated with non-vegetated permeable surfaces, as capable of strengthening the city's cooling capacity during heatwave episodes (Haselbach et al., n.d.; Iungman et al., 2023; Parison et al., 2020; Wu et al., 2021). These areas correspond to small public green spaces distributed heterogeneously throughout the urban matrix, which are mainly occupied by scattered shrubs, grasslands, a mix of medium and low-height vegetation with scattered or isolated trees, and small parks with irrigation and diverse surface composition. The results suggest the potential suitability of these spaces for mitigating the effects of heat waves, not only due to their green components but also due to the crossed interaction with other human-introduced permeable materials (such as pervious surfaces, sand, silt, or clay materials) (Bartesaghi-Koc et al., 2020, 2019), which could potentially enhance even more the cooling capacity in busy- and space-limited urban areas (Hayes et al., 2022; Vujovic et al., 2021). It is worth highlighting the added value that the "Other" area type can provide Mediterranean med-sized compact cities, since being distributed throughout the entire city, they act as rest areas and shelter locations in touristic and historic locations during heat wave episodes (Rosso et al., 2022; Terkenli et al., 2020).

It should also be noted that he heterogeneity in LST values across the whole urban area highlights the need to address the current challenge to alleviate the impacts of heat waves through sustainable measures. In this context, green planning is presented as a key mechanism to enhance microclimate conditions (Dzyuban et al., 2022; Hobbie and Grimm, 2020; Leal Filho et al., 2021), in which the role of green spaces, like the "Other" area type, would ameliorate the impact of heat waves as much as larger and greener areas (Dousset et al., 2011; Oliveira et al., 2011; Segura et al., 2023).

5. Conclusions

This study presents relevant information on how the small green spaces distributed throughout the city, defined as "Other" areas, would potentially help ameliorate the effects of heat waves heat wave episodes in medium-sized compact cities of the Mediterranean region. The analysis per type of green space revealed that this area type registered the lowest LST average values. "Other" areas show a stronger negative correlation in all heat wave episodes, which would indicate a better cooling capacity of these green spaces against extreme temperatures during heat wave episodes. A stronger negative correlation was also found between NDVI and LST data for the "Other" area type per episode, which would be consistent with their potential to strengthen the buffer capacity against the impacts of warm spells.

The potential buffer capacity observed in the "Other" area type during heat wave episodes fosters the need to identify the composition of those small public green spaces distributed heterogeneously throughout the urban matrix, and to understand how their components contribute to the city´s cooling capacity enhancement. This finding can be particularly relevant for Mediterranean cities, where highly limited space in city centers hinders the expansion of UGI areas or the creation of new ones to increase the cooling capacity during heat wave episodes. In regard to the composition of these areas, it would be relevant further research how heat wave impacts could be reduced by those human-introduced permeable materials that do not require irrigation to facilitate evapotranspiration and are easy to maintain given the climate conditions and water scarcity in the Mediterranean region.

Finally, the study promotes the idea that Mediterranean cities would find valuable benefits in green planning measures through the management of the "Other" area type; a more enhanced role of this area type would benefit cities during extreme high temperature events. This is not only due to the discussed environmental benefits, but also because of their potential effects at the micro-scale level on citizen health, thermal comfort, social interactions, energy demands, micro-economy, and quality of life.

Author Contributions: Conceptualization: M.J.D.-C.; methodology: M.J.D.-C. and P.C.; software: M.J.D.-C. and M.E.-V.; validation: M.J.D.-C. and P.C.; formal analysis: M.J.D.-C., P.C. and M.E.-V.; investigation: M.J.D.-C. and P.C.; resources: M.J.D.-C.; data curation: M.J.D.-C. and M.E.-V.; writing—original draft preparation: M.J.D.-C.; writing—review and editing: M.J.D.-C. and P.C.; visualization: M.J.D.-C.; supervision: M.J.D.-C. and P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Pre-competitive Research Projects University of Granada Own Plan, through the project PP2022. PP.34, Pre-GREENMITIGATION3.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: [https://www.usgs.gov/ (accessed on 30 November 2022); https://www.juntadeandalucia.es/ (accessed on 30 October 2022).

Acknowledgments: The authors would like to thank the Spanish National Geographic Institute, the Andalusian Environmental Information Network, Junta de Andalucía, and the U.S. Geological Survey for the spatial data and cartographic base provided for case of study.

Appendix

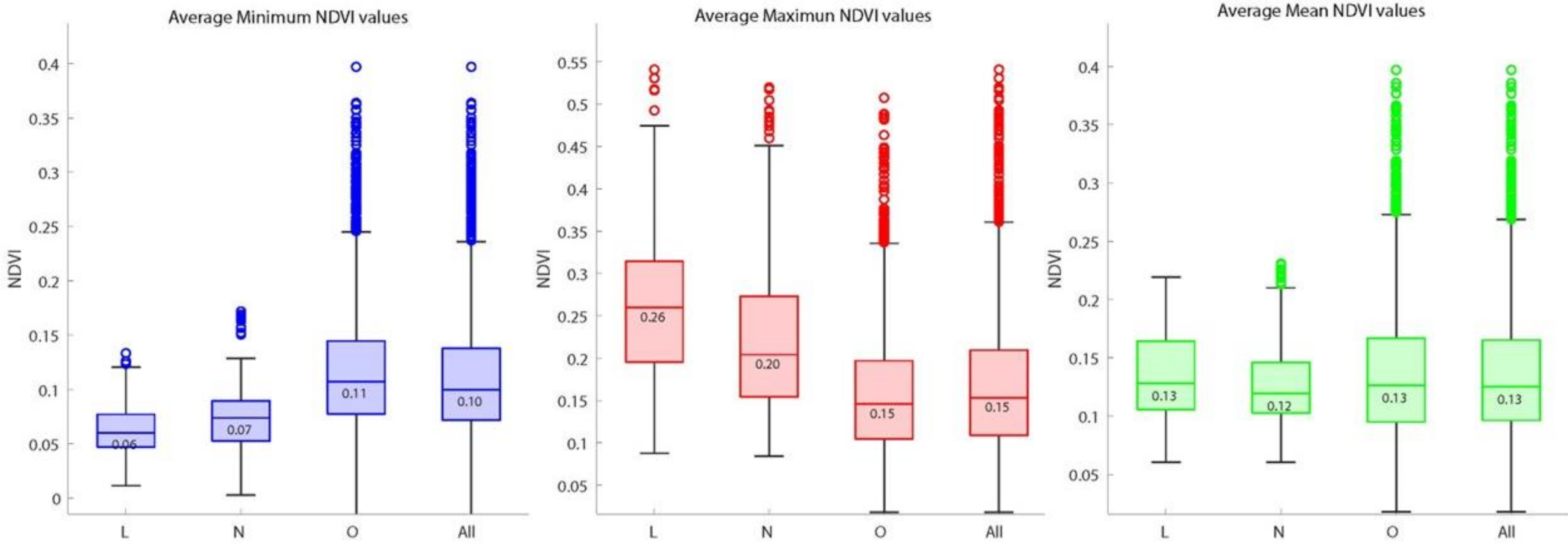
Appendix A - Test of Normality for LST and NDVI retrieved data.

Tests of Normality

Variable	HW Episode	Kolmogorov-Smirnov[a]		
		Statistic	df	Sig.
LST	All Episodes	0,077	3564	<0,001
NDVI	All Episodes	0,073	3564	<0,001
LST	2017/1	0,072	396	<0,001
LST	2018/5	0,051	396	0,015
LST	2019/6	0,049	396	0,023
LST	2019/7	0,06	396	0,002
LST	2020/8	0,058	396	0,003
LST	2020/9	0,066	396	<0,001
LST	2021/10	0,058	396	0,003
LST	2022/11	0,059	396	0,002
LST	2022/12	0,065	396	<0,001
NDVI	2017/1	0,092	396	<0,001
NDVI	2018/5	0,09	396	<0,001
NDVI	2019/6	0,078	396	<0,001
NDVI	2019/7	0,103	396	<0,001
NDVI	2020/8	0,099	396	<0,001
NDVI	2020/9	0,094	396	<0,001
NDVI	2021/10	0,079	396	<0,001
NDVI	2022/11	0,058	396	0,003
NDVI	2022/12	0,057	396	0,003

a. Lilliefors Significance Correction

Appendix B - NDVI mean value per are type in all periods. Whiskers determine the extent of the data inliers. Circles represent outliers.



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3.3. Assessing the Relationship between Land Surface Temperature and Composition Elements of Urban Green Spaces during Heat Waves Episodes in Mediterranean Cities

Revista: Forests, 2024.

Volumen: 15(3):463

DOI: https://doi.org/10.3390/f15030463

URL: https://www.mdpi.com/1999-4907/15/3/463

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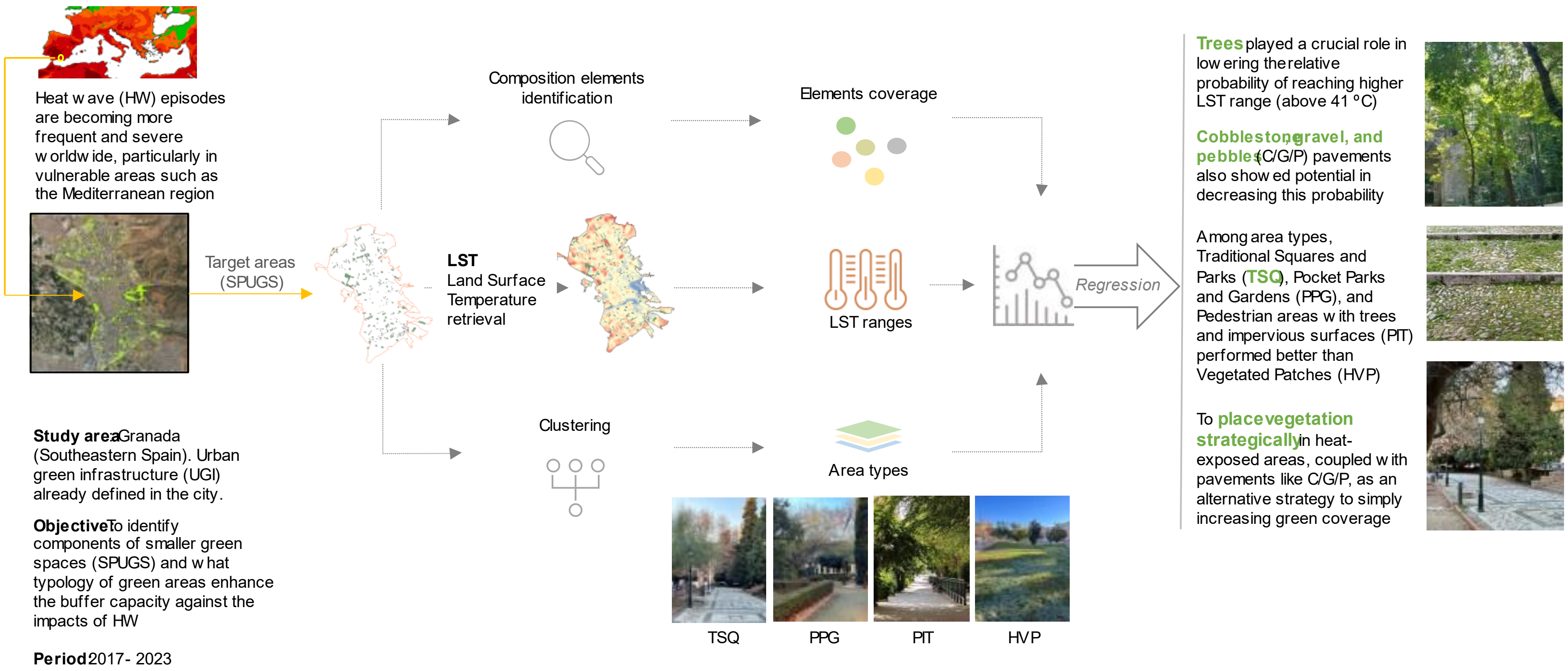
Graphical abstract



Abstract

In the context of escalating global temperatures and intensified heat waves, the Mediterranean region emerges as a noteworthy hotspot, experiencing a surge in the frequency and intensity of these extreme heat events. Nature-based solutions, particularly management of urban green infrastructure (UGI) areas, have shown promising outcomes in adapting urban areas to the challenges posed by heat waves. The objective of the current study is twofold: firstly, to identify the compositional patterns of strategically distributed small public green spaces, demonstrating their enhanced capacity to mitigate the impact of heat waves in the Mediterranean region; secondly, to assess the association, direction, and explanatory strength of the relationship between the composition elements of the UGI areas and area typology, specifically focusing on the variation in land surface temperature (LST) values during heat wave episodes spanning from 2017 to 2023. The methodology involved obtaining land surface temperature (LST) values from satellite images and classifying green areas based on composition, orientation, and typology. Ordinal multiple regressions were conducted to analyze the relationship between the considered variables and LST ranges during heat wave episodes that occurred from 2017 to 2023. The findings indicate an increase in LST ranges across many areas, emphasizing heightened thermal stress in a Mediterranean medium-sized compact city, Granada (in the southeast of the Iberian Peninsula). Traditional squares, pocket parks and gardens, and pedestrian areas with trees and impervious surfaces performed better in reducing the probability of exceeding LST values above 41 °C compared to other vegetated patches mainly occupied by herbaceous vegetation and grass. The study concludes by advocating for the strategic incorporation of vegetation, especially trees, along with traditional squares featuring semipermeable pavement with trees and shrubbery, as a potential effective strategy for enhancing resilience against extreme heat events. Overall, this research enhances our understanding of LST dynamics during heat waves and offers guidance for bolstering the resilience of urban green spaces in the Mediterranean region.

1. Introduction

Escalating global temperatures and the heightened frequency and intensity of heat waves (HWs) have become prominent focal points in climate change research, with significant implications for health, energy, and ecological aspects (Breshears et al., 2021; Marx et al., 2021; Santamouris, 2020). Officially confirmed by international datasets as the warmest year on record, 2023 underscores the urgency of addressing these climatic shifts (“Data.GISS: GISS Surface Temperature Analysis (GISTEMP v4),” n.d., “World Meteorological organization,” n.d.). The latest Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report highlights the robust evidence of increased warm days and extreme temperatures globally, with a particular emphasis on HWs in the southern Mediterranean (IPCC, 2022).

In this context, the Mediterranean region stands out as a heat hotspot, experiencing a rising trend in the average intensity and frequency of HWs, along with an increase in minimum temperatures (Hochman et al., 2018; Perkins-Kirkpatrick and Lewis, 2020; Wedler et al., 2023). In particular, this forecast has direct effects, especially in urban areas, which, among other impacts, result in heat stress and related issues detrimental to human well-being (Donateo et al., 2023; Hochman et al., 2022; Lange, n.d.). Notably, higher surface temperature values are associated with increased risk of mortality and morbidity during heat waves (Cuerdo-Vilches et al., 2023; Royé et al., 2020; Song et al., 2024). In this context, green areas can play a crucial role in outdoor environments, effectively mitigating high temperatures and providing a protective shield against heat-related impacts (López-Bueno et al., 2020). The significance of green spaces becomes particularly evident in Mediterranean climate cities, as revealed by a health impact assessment conducted by Iungman et al. (2023). That study showed how cities with low cooling index scores, such as Athens, Valencia, Seville, Palermo, Málaga, and Madrid, experienced elevated mortality rates due to heat stress. Specifically, the effect of summer on annual attributable deaths (95% CI) ranged from 12.39% in Málaga to 14.82% in Barcelona. Moreover, an increase in tree coverage demonstrated its potential to generate a notable decrease in summer preventable deaths, as seen in Murcia with a reduction of 29.85% (95% CI) (Iungman et al., 2023). Additionally, previous research in the Mediterranean region emphasizes effective and very specific strategies at different scales to face these challenges. At the microscale level, establishing and promoting habitable spaces, such as courtyards, and implementing shading strategies have demonstrated positive outcomes during HW episodes (Diz-Mellado et al., 2021; Natanian et al., 2020). Increasing green spaces with vegetation at a local level has also been demonstrated as a successful measure (Hidalgo-García and Arco-Díaz, 2022). Ultimately, applicable across all scales within urban areas and serving as more comprehensive strategies to adapt and mitigate the impacts of HWs, are nature-based solutions (Kumar et al., 2020; Panagiotakis et al., 2021). As a nature-based solution, management of urban green infrastructure (UGI) areas provides highly effective outcomes in adapting urban areas to the anticipated challenges posed by future HWs (Perini et al., 2022). While increasing vegetation and greening strategies in UGI areas represent a well-fitted adaptation and mitigation strategy, additional research becomes crucial to determine the most suitable UGI for specific urban areas to strengthen the buffer capacity against the impacts of warm spells (Maggiotto et al., 2021; Santamouris and Osmond, 2020).

In a recent study conducted by Delgado et al. in 2023, an in-depth investigation into the cooling capacity of green spaces during HW episodes was undertaken (Delgado-Capel et al., 2023). This involved a meticulous examination of the correlation between land surface temperature (LST) and the Normalized Difference Vegetation Index. Despite some existing pitfalls in the literature that suggest a potential link between "warm surfaces" and "high air temperatures", particularly in urban heat-island-related studies, LST is considered a reliable proxy for air temperature and thermal comfort (Benali et al., 2012; Coutts et al., 2016; Do Nascimento et al., 2022; Zhang et al., 2014). In addition to the quantity, health, and type of vegetation, LST values respond to urban land surface properties by detecting variations in spectral reflectance between built-up or impervious surfaces and the brightness of surface or bare soil cover (Guo et al., 2020). Building upon this understanding, the premise of the current study is grounded. It posits that small green spaces strategically distributed across urban areas could play a pivotal role in mitigating the impacts of HW episodes, especially in medium-sized compact cities within the Mediterranean region. In Delgado et al. (2023), these smaller green spaces exhibited greater cooling capacity against extreme temperatures during HWs compared to medium-sized patches (with extensions ranging from 10,000 m2 to 100,000 m2), including small forests, dense shrubs, grasslands, or parks. Additionally, they showed better cooling capacity compared to areas with linear spatial distributions that connect larger-sized patches (with extensions exceeding 100,000 m2), such as urban forests, to medium-sized ones. While it is commonly acknowledged that larger urban parks exhibit a higher cooling effect intensity, as indicated by the temperature difference compared to vegetation-free urban areas (Aram et al., 2019), smaller urban green spaces stand out for their capability to extend cooling effects over a greater distance than some larger areas, which enhances benefits at the microsite level, such as within neighborhoods or residential clusters (Gallay et al., 2023; Peng et al., 2021). These smaller green spaces have the potential to significantly and effectively reduce the LST in their surroundings, contributing to the improvement in the urban thermal environment, particularly in high-density urban settings (Wu et al., 2021). With this backdrop, optimizing the cooling effects of these small urban green spaces requires a detailed understanding of their types and composition elements (Park et al., 2017). However, the design and composition elements of these UGI assets poses challenges, encompassing factors such as adaptability to extreme (Hayes et al., 2022), sudden, and fluctuating weather conditions, and considerations of the physical footprint (Jayasooriya et al., 2020; Semeraro et al., 2021), potential ecosystem disservices (Cariñanos et al., 2020), accessibility (Kronenberg et al., 2020), or the influence of size and design on perceived well-being (Reyes-Riveros et al., 2021).

In this context, the primary objective of the current study is twofold. Firstly, it aims to identify the compositional patterns of small public green spaces scattered heterogeneously throughout the urban matrix, showcasing enhanced capacity to ameliorate the impact of HWs in the Mediterranean region, as indicated by previous research (Delgado-Capel et al., 2023). Secondly, this study aims to evaluate the association, direction, and explanatory strength in the relationship between the composition elements of the UGI areas under study and the area typology, concerning the variation of LST values during HW episodes spanning from 2017 to 2023. Finally, the research strives to elucidate which components of these smaller green areas and what typology of green space enhance the buffer capacity against the impacts of warm spells, thereby providing valuable insights into the ongoing discourse on urban heat mitigation strategies.

2. Materials and Methods

2.1. Study area.

Granada is a representative medium-sized compact city of the Mediterranean region located in the southeast of the Iberian Peninsula (37.179937, −3.603489; 680 m. a.s.l.). In the urban area of Granada, an excessive coverage of built-up areas can be observed, with a 12.42% increase between 2002 and 2022 (Hidalgo-García and Arco-Díaz, 2022). The average percentage of the built-up area in 2022 varied from 39.37% in areas characterized by high-density urban fabric to 87.28% in the dense urban core (Hidalgo García, 2023). It presents a Mediterranean–continental climate, with an average annual temperature of 15.2 °C for the period of 1985–2014 (which is projected to increase to 16.8 °C by 2050) ("Clima de Andalucia," n.d.). The Köppen–Geiger climate classification for Granada is Csa, which corresponds to a Mediterranean climate characterized by dry and hot summers (Andrade and Contente, 2020; "World Maps of Köppen-Geiger climate classification," n.d.). Since 1975, Granada has been significantly impacted by heat waves, exhibiting the highest recurrence rate of these events since 2011 among Spanish cities (AEMET, 2023).

Of the 341 areas within Granada's urban green infrastructure (UGI), this study specifically concentrated on the analysis of smaller public urban green spaces classified as "Other" areas (Delgado-Capel and Cariñanos, 2020). It is important to note that a portion of these areas (14.07%) exceeds the characteristic size limit set for a small public urban green space (SPUGS), which is defined as an area below 5000 m2 (Peschardt et al., 2012) (Figure 1).

2.2. Heat Wave identification and Land Surface Temperature retrieval.

This research adopted the heat wave (HW) definition given by the Spanish Agency of Meteorology (AEMET) as an episode lasting at least three consecutive days, during which at least 10% of the considered weather stations record maximum temperatures above the 95th percentile of their daily maximum temperature series for the months of July and August during the 1971–2000 period ("Olas de calor en España desde 1975 Área de Climatología y Aplicaciones Operativas," n.d.).

Land surface temperature (LST) values in daylight hours for each target area were obtained from a previous study by Delgado-Capel et al. (2023) (Delgado-Capel et al., 2023) using Landsat 8 and 9 OLI/TIRS satellite images derived from the U.S. Geological Survey ("Landsat Normalized Difference Vegetation Index | U.S. Geological Survey," n.d.). To address the stated objectives, in this study, we selected maximum LST values based on the consideration of the cumulative adverse impacts of higher temperatures during extreme heat episodes (Mazdiyasni et al., 2019; Shi et al., 2021). The LST datasets were updated with the latest data corresponding to the HWs identified in 2023 ("Olas de calor en España desde 1975 - Agencia Estatal de Meteorología - AEMET. Gobierno de España," n.d.). A total of 16 episodes were identified, among which LST retrieval was only possible in 11 of them. This limitation arose due to the absence of Landsat images on required dates or cloud coverage obstructing the proper LST retrieval over the target areas within the urban matrix (Table 1).

Land surface temperature (LST) values were recoded into specific ranges to facilitate a comprehensive understanding of their distribution and their association with areas prone to discomfort due to heat stress. To carry out this recoding, this study supported the approach on the significant correlation between LST, air temperature, and the Physiological Equivalent Temperature (PET) (Goldblatt et al., 2021; Kalogeropoulos et al., 2022). PET is among the most widely employed thermal indices in urban settings, renowned for its ability to intricately consider complex urban geometries and surfaces and its applicability in studies assessing the impact and perception of heat waves in cities (Gómez et al., 2013; Lai et al., 2019). The adopted recoding of LST values was aligned with the indicative PET thresholds for regions similar to our study area, in which temperatures below 35 °C trigger a moderate heat stress (warm thermal sensation), while temperatures exceeding 41 °C trigger extreme heat stress (very hot thermal sensation) (Höppe, 1999; Rodríguez-Algeciras et al., 2020; Salata et al., 2016). Prior research conducted in the Mediterranean region employed intervals of 2 degrees for setting up the ranges (Cheung and Jim, 2017; Potchter et al., 2018). Therefore, LST values were eventually recoded into 5 ranges, as shown in Table 2.

HW [1] Episode	Start–End Dates	Duration	Data Source [2]	Date Acquired	Scene Center Time (GMT+1) [3]
HW 1	13–21 June 2017	9 days	Landsat 8 (OLI/TIRS)	19 June 2017	11:49:55
HW 2	12–16 July 2017	5 days	Landsat 8 (OLI/TIRS)	Not available on required dates	
HW 3	28–30 July 2017	3 days	Landsat 8 (OLI/TIRS)	Not available on required dates	
HW 4	2–6 August 2017	5 days	Landsat 8 (OLI/TIRS)	Cloud cover above the urban matrix	
HW 5	31 July–7 August 2018	8 days	Landsat 8 (OLI/TIRS)	9 August 2018	11:49:50
HW 6	26 June–1 July 2019	6 days	Landsat 8 (OLI/TIRS)	25 June 2019	11:50:04
HW 7	20–25 July 2019	6 days	Landsat 8 (OLI/TIRS)	18 July 2019	11:56:19
HW 8	25 July–2 August 2020	9 days	Landsat 8 (OLI/TIRS)	29 July 2020	11:50:08
HW 9	6–8 August 2020	5 days	Landsat 8 (OLI/TIRS)	5 August 2020	11:56:20
HW 10	11–16 August 2021	6 days	Landsat 8 (OLI/TIRS)	17 August 2021	11:50:21
HW 11	12–18 June 2022	7 days	Landsat 9 (OLI/TIRS)	9 June 2022	11:49:43
HW 12	9–26 July 2022	18 days	Landsat 8 (OLI/TIRS)	19 July 2022	11:50:28
HW 13	9–12 July 2023	4 days	Landsat 8 (OLI/TIRS)	Not available on required dates	
HW 14	17–20 July 2023	4 days	Landsat 8 (OLI/TIRS)	Cloud cover above the urban matrix	
HW 15	6–13 August 2023	8 days	Landsat 8 (OLI/TIRS)	7 August 2023	11:50:03
HW 16	17–25 August 2023	9 days	Landsat 8 (OLI/TIRS)	23 August 2023	11:50:11

Table 1. Heat wave episode information and Landsat image details. [1]: HW#: Heat wave episode; [2]: OLI/TIRS: Operational Land Imager Thermal Infrared Sensor; [3]: GMT: Global Meridian Time.

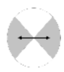
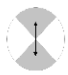
Land Surface Temperature (LST)		Percentage Coverage of Composition Elements			Orientation		
LST Interval (°C)	LST Range	Variables		Intervals of Cover Percentage (%)	Major Axis Orientation	Assignation [6]	
<35.00	LST Range 1	Tree	Imp. Surf. [4]	**1**: 0–20.00	45.01° to 135.00°	EW	
35.01–37.00	LST Range 2	Shrub	Build	**2**: 20.01–40.00			
37.01–39.00	LST Range 3	Herb/Grass [1]	C/G/P [5]	**3**: 40.01–60.00	225.01° to 315.00°		
39.01–41.00	LST Range 4	Soil [2]	Water	**4**: 60.01–80.00	315.01° to 45.00°	NS	
>41.01	LST Range 5	Perv. Surf. [3]		**5**: 80.01–100	135.01° to 225.00°		

Table 2. Summary of variable recoding: ranges of land surface temperature values, intervals of cover percentage for composition elements, and orientation assigned to the target areas based on their major axis. [1]: Herb/Grass: herbaceous species and grasses; [2]: Soil: bare soil; [3]: Perv. Surf.: pervious surfaces; [4]: Imp. Surf.: impervious surfaces; [5]: C/G/P: cobblestone, gravel, and pebble; [6]: EW: East–West, NS: North–South.

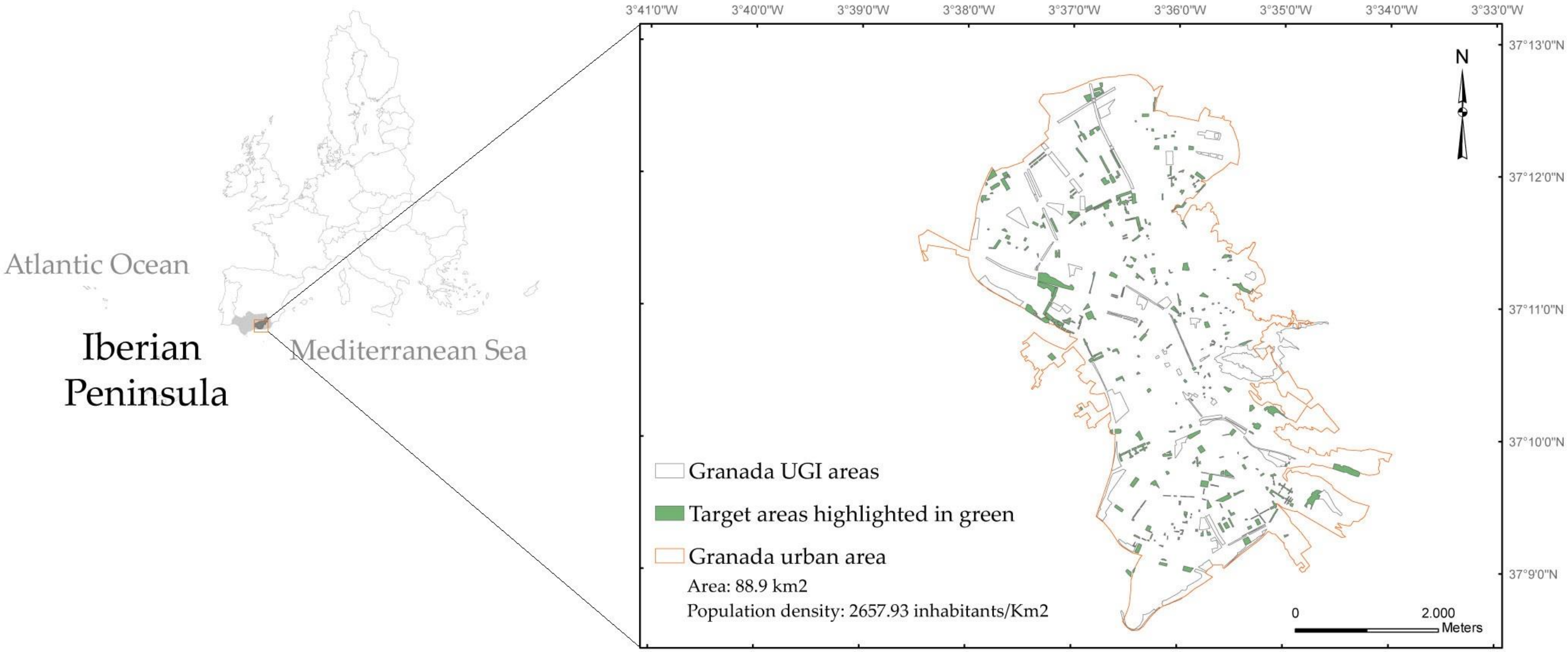


Figure 1. Smaller urban green spaces within the urban green infrastructure of the study area.

2.3. Composition and Orientation of target areas.

The composition of elements within the target areas, included trees, shrubs, surfaces with herbaceous species and grasses, bare soil, pervious surfaces (such as sands or silts), impervious surfaces (such as asphalt, concrete, construction tiles or rubberized surfaces), buildings, and water surfaces (mainly found in square fountains). In addition, semipermeable pavement was included as a structural component, as it is a type of surface widely found in parks and squares of compact medium- and small-sized cities in the Mediterranean region due to its historical heritage (Kullmann, 2020). This type of surface mainly combines rounded pebbles, cobblestones, or gravel with permeable interstitial spaces.

The identification of composition elements was performed by calculating the percentage coverage for each composition element in every target area with ARCGIS 10.6 software. This process involved visualizing and identifying each composition element within each target area using high-resolution aerial orthophotography coverage from the National Aerial Orthophotography Plan ("Plan Nacional de Ortofotografía Aérea," n.d.). This exhaustive and manual identification allowed us to overcome the existing challenges in land cover mapping and processing at this resolution (MohanRajan et al., 2020), including accuracy limitations in distinguishing certain categories (e.g., dry grass or bare soil vs. concrete, trees vs. irrigated grass, or roofs vs. asphalt) (Hiscock et al., 2021) and potential issues with supervised learning techniques not providing fully ground-truth labels (Schmitt et al., 2020; Zhou, 2018). Subsequently, each target area was assigned a range of coverage percentage for each composition element, to enhance data simplicity and control over variability, and to improve overall manageability and interpretability of results. The percentage coverage of elements was recoded into 5 ranges: 1 = 0%–20%, 2 = 20.01%–40%, 3 = 40.01%–60%, 4 = 60.01%–80%, and 5 = 80.01%–100% (Table 2).

Finally, the orientation of the target areas was determined based on the position of the major axis of each area. Thus, areas with their major axis oriented between 45 and 135 degrees, and from 225 to 315 degrees, were assigned an East–West orientation. Conversely, areas with their major axis oriented from 315 to 45 degrees, and from 135 to 225 degrees, were assigned a North–South orientation (Table 2).

2.4. Statistical analysis.

Ordinal regressions were computed for analyzing the effect of SPUGS components, orientation, and type (as independent variables) on LST ranges (as dependent variables). To test the association, direction, and strength of each composition and orientation variables in the explanatory power of the LST range reached in each event, 12 multiple ordinal regressions were modeled, one for each HW episode with available data and another one with the mean value of all episodes.

To analyze the association, direction, and strength of the relationship of SPUGS' composition, orientation, and typology with LST ranges, 12 ordinal multiple regressions were modeled, one for each HW episode with available data and another one with the average value of all episodes. In each case, the dependent variable was the LST value collected in each HW episode recoded in segments and the independent variables were the recoded percentages of cover composition element and orientation. To test the levels of explanatory power of each model with respect to the null model, the Cox and Snell, and Nagelkerke and McFadden pseudo R-squared were used (Cucchiara, 2012; Maalouf, 2011).

Subsequently, the composition element variables were grouped into type of SPUGS using the K-means clustering technique. To determine the number of clusters to extract, the elbow method was used, observing the loss of internal heterogeneity as the number of retained clusters increases. Where the slope decreases steeply, it is determined as the number of clusters to be obtained. Subsequently, the means of the variables in each cluster were analyzed, as well as the relationship of the clusters with the rest of the variables using chi-square and Haberman's corrected standardized residuals analysis, in order to name and interpret the type of SPUG under assessment.

Finally, with the intention of providing aggregate information on what type of SPUG reduces or increases to a greater extent the probability of reaching higher LST ranges, 12 new multiple ordinal regressions were performed in which the independent variables were each cluster, and each of the dependent variables comprised the LST values recoded in segments. The statistical analysis for this research was conducted using IBM SPSS Statistics software, version 28.0.0.0 (190).

3. Results

3.1. Land Surface Temperature assessment.

Data on land surface temperature (LST) were collected for 11 episodes spanning from 2017 to 2023, along with the overall mean for all episodes. The least intense HW episode was the latest recorded in 2019 (HW7), with a mean LST value of 32.53 °C across all areas. The highest mean LST value occurred in the first episode of 2020 (HW8), reaching 41.10 °C. Following this episode, LST mean values surpassed those of the initial episodes from 2017 and 2018 (HW1, HW5, and HW6), ranging from 39.12 °C in episode HW12 to 39.85 °C in the last episode recorded in 2023 (HW16). The overall mean LST across all episodes was 37.94 °C (Figure 2).

The distribution of LST values within the adopted recoding ranges illustrates that LST Range 3 (values between 37.01–39.00 °C) and LST Range 4 (values between 39.01–41.00 °C) accumulated the highest percentage of areas falling within these ranges. In alignment with the average LST values per episode, 96.19% of the studied areas exhibited values below 35 °C in the latest HW episode recorded in 2019 (HW7). Conversely, in the hottest episode (HW8), 95.01% of the areas registered LST values above 39.01 °C, with 43.40% falling within LST Range 4 (values between 39.01–41.00 °C) and 56.61% within LST Range 5 (values above 41 °C). Considering all episodes, most of the studied areas (65.40%) recorded values between 37.01 and 39.00 °C (LST Range 3) (Table 3).

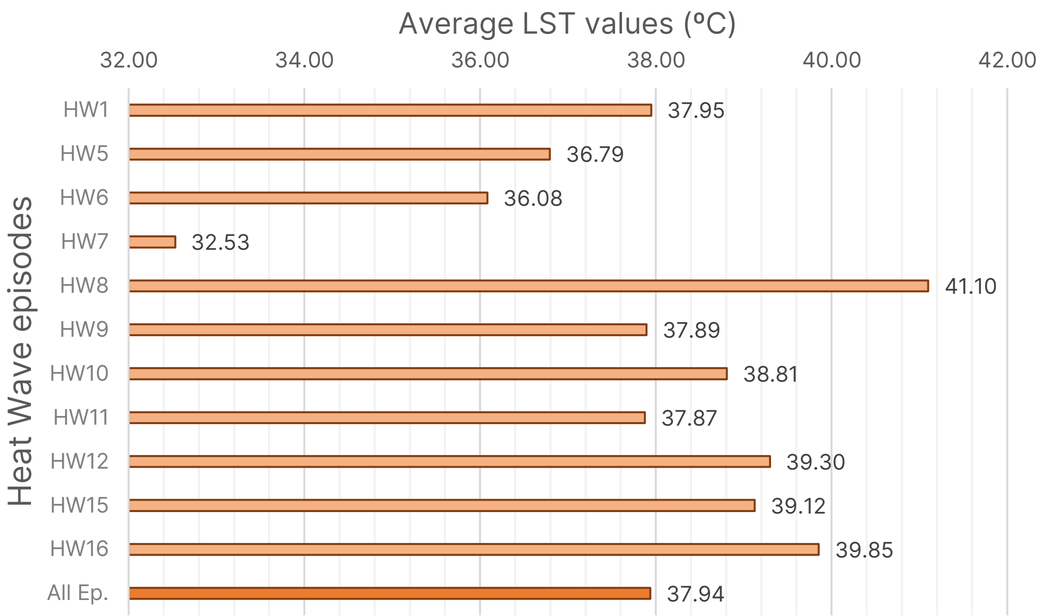


Figure 2. Average of retrieved LST values per heat wave (HW) episode and all episodes over the target areas.

	LST Range 1	LST Range 2	LST Range 3	LST Range 4	LST Range 5
HW1	1.76%	17.89%	65.10%	10.85%	4.40%
HW5	6.16%	53.37%	35.48%	2.93%	2.05%
HW6	17.89%	64.22%	13.78%	2.93%	1.17%
HW7	96.19%	2.64%	0.59%	0.59%	0.00%
HW8	0.00%	1.17%	3.81%	43.40%	51.61%
HW9	2.64%	24.63%	57.77%	10.56%	4.40%
HW10	0.59%	3.81%	56.89%	32.84%	5.87%
HW11	0.88%	23.46%	62.46%	9.38%	3.81%
HW12	0.29%	2.05%	37.54%	52.79%	7.33%
HW15	0.29%	3.52%	46.04%	42.82%	7.33%
HW16	0.29%	2.05%	24.63%	54.84%	18.18%
All Ep.	0.88%	20.23%	65.40%	11.44%	2.05%

Table 3. Percentage of areas within the adopted land surface temperature (LST) ranges. LST Range 1: <35.00 °C; LST Range 2: 35.01–37.00 °C; LST Range 3: 37.01–39.00 °C; LST Range 4: 39.01–41.00 °C; LST Range 5: >41.01 °C.

3.2. Information on composition elements and clustering result.

In the identification of composition elements within the target areas, the most prevalent element was the impervious surface, with an average coverage percentage of 39.24% across all areas. Over 50% of areas with impervious surface presence exhibited less than 40.00% coverage. Trees showed a mean coverage of 27.25%, with 42.52% of areas having up to 20.00% tree coverage and 35.48% with coverage between 20.01% and 40%. The rest of the vegetated composition elements, shrub and herbaceous species/grasses had average coverages of 7.47% and 9.78%, respectively, with 87.89% and 81.52% of areas having up to 20% coverage for shrubs and herbaceous species/grasses. Pervious surface had a mean coverage of 9.32%, with 79.77% of areas having up to 20% coverage. Semi-impermeable surfaces (cobblestone, gravel, pebble) averaged 4.34% and their presence in all areas was under 20.00% coverage. Bare soil had a mean coverage of 2.12%, present in 97.65% of areas with less than 20% coverage. Buildings showed a limited presence (0.44% average coverage), and water had a negligible presence (0.06% average coverage) in 100% of areas, with water presence not exceeding 3% of the total green area in any case (Table 4).

Composition Element [1]	Tree	Shrub	Herb./Grass	Soil	Perv. Surface	Imp. Surface	Build	C/G/P	Water
Avg. All [2]	27.25%	7.47%	9.78%	2.12%	9.32%	39.24%	0.44%	4.34%	0.06%
Intervals of cover%	% of areas within each interval								
1: 0–20.00	42.52%	87.98%	81.52%	97.65%	79.77%	35.78%	99.41%	100.00%	100.00% [3]
2: 20.01–40.00	35.48%	9.09%	9.97%	0.59%	12.90%	15.25%	0.59%	0.00%	0.00%
3: 40.01–60.00	13.49%	2.64%	2.93%	0.59%	3.81%	19.65%	0.00%	0.00%	0.00%
4: 60.01–80.00	3.81%	0.29%	1.76%	0.59%	2.93%	17.30%	0.00%	0.00%	0.00%
5: 80.01–100%	4.69%	0.00%	3.52%	0.59%	0.59%	11.73%	0.00%	0.00%	0.00%

Table 4. Composition element assessment. [1]: Composition elements: Herb/Grass: herbaceous species and grasses; Soil: soil and bare ground; Perv. Surf.: pervious surfaces; Imp. Surf.: impervious surfaces; C/G/P: cobblestone, gravel, and pebble; [2]: Cover average of each composition element in all areas. [3]: Presence of water in only 16 areas, under 3% of the total area surface and less than 100 m^2 in all cases.

The clustering of target areas resulted in four distinct types defined by their composition elements (Figure 3, Table 5):

- Traditional squares and parks (TSQ) typically formed by a semipermeable pavement composed of light-colored cobblestones, gravel, or pebbles and with the presence of trees and small scattered garden areas with shrubbery.
- Parks and garden areas (PPG) mainly occupied by trees with hedge gardens and a combination of impervious and pervious pavements. This type includes pocket parks, walking paths, playgrounds, or sports fields.

- Pedestrian and transit areas (PIT) distributed throughout the city characterized by a combination of trees and predominantly impervious pavements like tails, asphalt, concrete, and in some cases, rubberized surfaces.
- Vegetated patches and public areas (HVP) for ornamental or structural purposes, with scattered trees and shrubs, mainly occupied by herbaceous vegetation and grass.

Upon defining the area types through clustering, additional analysis included calculating the average LST value for each cluster across all episodes. The lowest average LST was observed in TSQ areas (36.75 °C), whereas PIT and PPG areas exhibited quite similar values (37.44 °C and 37.43 °C, respectively). Finally, HVP areas showed the highest average LST values across all episodes, with a value of 37.63 °C (Figure 3).

Composition Element	Defined Area Type after Clustering			
	TSQ	PPG	PIT	HVP
Tree	14.52%	42.07%	18.95%	10.55%
Shrub	5.72%	9.19%	6.09%	8.08%
Herbaceous/Grass	0.27%	6.77%	2.17%	73.43%
Soil	0.17%	4.48%	0.47%	1.27%
Pervious surface	0.68%	18.95%	3.34%	2.05%
Impervious surface	5.64%	17.41%	67.92%	3.97%
Build	0.04%	0.14%	0.69%	0.67%
Water	0.04%	0.09%	0.11%	0.00%
Cobblestone/gravel/pebble	72.93%	0.98%	0.22%	0.00%

Table 5. Percentage average of composition elements per defined area type. TSQ: Traditional squares; PPG: Pocket Parks and gardens; PIT: Pedestrian areas mainly covered by impervious surfaces and trees; HVP: herbaceous and grass vegetated patches.

3.3. *Regression Results.*

The ordinal regression analysis examining the relationship between ranges of maximum LST values and composition elements demonstrated statistically significant ($p < 0.05$) model fitting information across most episodes, except for episode 8. Estimates with a significance level of <0.05 showcased distinct relationships between these two variables accordingly (Table 6).

Figure 3. Area types resulting from clustering and examples. TSQ: Traditional squares; PPG: Parks and garden areas (PPG); PIT: Pedestrian and transit areas; HVP: Herbaceous vegetated patches.

Episode; MFI Sig.			HW1 **	HW5 **	HW6 **	HW7 ***	HW8	HW9 **	HW10 *	HW11 **	HW12 *	HW15 ***	HW16 ***	All Ep. **
Threshold	LST Range 1		−8.16	−2.60	−6.31	−35.13		−9.19	−5.85	−1.50	−4.36	−8.89	−9.58	−7.36
Threshold	LST Range 2		−5.54	0.66	−3.05	−33.88	−4.33	−6.54	−3.79	2.11	−2.26	−6.29	−7.47	−3.93
Threshold	LST Range 3		−2.15	3.34	−1.33	−33.17	−2.84	−3.62	−0.14	5.30	1.11	−2.94	−4.70	−0.51
Threshold	LST Range 4		−0.58	4.21	0.18		0.12	−2.20	2.45	6.76	4.16	−0.19	−1.99	1.54
Location	Tree	Model Parameters (β)	−0.51 *	0.00	−0.57 *	−1.83 *	−0.08	−0.54 *	−0.26	0.00	0.06	−0.38 *	−0.40 *	−0.40 *
Location	Shrub	Model Parameters (β)	−0.51	−0.37	−0.53	−1.77	−0.39	−0.65 *	−0.24	−0.26	−0.29	−0.66 *	−0.67 *	−0.59
Location	Herb/Grass	Model Parameters (β)	0.01	0.15	−0.08	−0.65	0.32	−0.06	0.27	0.55 *	0.36	0.22	0.24	0.16
Location	Soil	Model Parameters (β)	−0.55	0.07	−0.52	−9.29	0.38	−0.26	−0.16	0.15	0.00	−0.43	−0.17	−0.32
Location	Perv. Surf.	Model Parameters (β)	−0.04	0.37	−0.06	−0.70	0.17	−0.08	0.14	0.29	0.23	0.05	0.11	0.16
Location	Imp. Surf.	Model Parameters (β)	−0.35	0.00	−0.35	−1.23 *	−0.02	−0.41 *	−0.11	0.16	−0.02	−0.14	−0.23	−0.25
Location	Build	Model Parameters (β)	−0.35	0.41	−0.64	−11.52	0.04	−1.62	0.28	1.96	1.28	−0.47	−1.42	−0.05
Location	C/G/P	Model Parameters (β)	−0.49 *	−0.43 *	−0.57 *	−7.44	−0.24	−0.47 *	−0.21	−0.04	−0.22	−0.41 *	−0.29	−0.37

Table 6. Ordinal regression analysis: estimates for LST range prediction based on composition elements. MFI: Model fitting information. * Sig. < 0.05; ** Sig. < 0.01; *** Sig. < 0.001.

Episode; MFI Sig.		HW1	HW5 **	HW6 *	HW7	HW8 *	HW9	HW10 *	HW11 **	HW12 **	HW15 **	HW16 **	All Ep. *
Threshold	LST Range 1	−4.92	−2.88	−2.20	2.16		−4.25	−6.18	−6.05	−6.63	−6.87	−7.02	−5.56
	LST Range 2	−2.29	0.38	0.92	3.38	−5.28	−1.61	−4.12	−2.43	−4.52	−4.26	−4.92	−2.14
	LST Range 3	0.94	2.97	2.62	4.07	−3.79	1.16	−0.50	0.74	−1.14	−0.96	−2.17	1.09
	LST Range 4	2.49	3.89	4.12		−0.84	2.57	2.05	2.17	1.87	1.65	0.41	3.12
Location (Model Parameters (β))	TSQ	−1.67	−1.79 **	−1.70 *	−20.13	−1.94 **	−1.44	−1.86 **	−2.16 ***	−1.99 **	−2.22 ***	−1.93 ***	−1.68 **
	PPG	−0.88	0.11	−0.60	−0.75	−0.79	−0.55	−0.99 *	−1.47 ***	−0.60	−1.06 *	−1.10 *	−0.74
	PIT	−0.91	0.04	−0.67	−1.79	−0.78	−0.67	−1.09 *	−1.18 **	−0.80 *	−0.88 *	−1.27 **	−0.88 *
	HVP	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]

Table 7. Ordinal regression analysis: estimates and model parameters for LST range prediction based on area type. MFI: Model fitting information. * Sig. < 0.05; ** Sig. < 0.01; *** Sig. < 0.001. a: parameter is set to zero because it is redundant.

Composition elements such as trees, shrubs, impervious surfaces and cobblestone, and gravel and pebble surfaces were identified as significant factors in predicting the variability in LST ranges. For every one-unit increase in any of these variables, a decrease in the ordered log odds of reaching the highest LST range (maximum values above 41 °C) was expected. The presence of trees exhibited a negative directional relationship in episodes HW1 (estimate: −0.51), HW6 (estimate: −0.57), HW7 (estimate: −1.83), HW9 (estimate: −0.54), HW15 (estimate: −0.38), and HW16 (estimate: −0.40). There was a predicted decrease of −0.40 in the logarithmic probability of reaching the highest LST range considering all episodes. Similarly, the presence of shrubs demonstrated a negative directional relationship in episodes HW9 (estimate: −0.65), HW15 (estimate: −0.66), and HW16 (estimate: −0.67). The presence of impervious surfaces exhibited a negative direction in episodes HW7 (estimate: −1.23) and HW9 (estimate: −0.41). Furthermore, presence of cobblestone, gravel, and pebble surfaces showed a consistent negative direction in episodes HW1 to HW6 (estimates: −0.49, −0.43, −0.57), HW9 (estimate: −0.47), and HW15 (estimate: −0.41), as well as a predicted decrease in the logarithmic probability (estimate: −0.41) of reaching the highest LST range in consideration of all episodes (Table 6).

In contrast, herbaceous vegetation and grass presence showed a positive directional relationship in episode HW11, indicating that for every range increase in herbaceous vegetation and grass as the area surface, there is a predicted increase of 0.55 in the relative probability of the LST range considered exceeding 41 °C. Estimates for the rest of the independent variables (bare soil, pervious surface, and building) did not show statistical significance in any of the models (Table 6). Water was excluded as a composition element in the regression models due to its virtually negligible presence in the study areas. Water was only present in 16 out of the 341 areas under investigation, and in none of these cases did the surface coverage percentage exceed 3% or 100 m2.

The models relating ranges of maximum LST values and type of area values exhibited model fitting statistical significance ($p < 0.05$) for every episode, except for episodes HW1, HW7, and HW9. In consideration of all episodes, statistical significance ($p < 0.05$) was also observed for the whole model. In this ordinal regression analysis, estimates for areas TSQ, PPG, and PIT showed statistically significant explanatory strength with the variability of LST ranges, compared to area type HVP (Table 7).

For TSQ areas, a negative directional relationship was observed, indicating a significant predicted decrease in the logarithmic probability of reaching the highest LST range in episodes HW5 (estimate: −1.79), HW6 (estimate: −1.70), HW10 (estimate: −1.86), HW11 (estimate: −2.16), HW12 (estimate: −1.99), HW15 (estimate: −2.22), and HW16 (estimate: −1.93). In episode HW8, a negative estimate (−1.94) showed a decrease in the relative probability of reaching the minimum LST range (up to 35 °C) and surpassing the highest one (over 41 °C). For PPG areas, results showed statistically significant negative estimates in episodes HW10 (−0.99), HW11 (−1.47), HW15 (−1.06), and HW16 (−1.10), indicating a decrease in the log odds of attaining Range 5 of maximum LST values compared to the reference area type. Results with statistical significance for PIT areas displayed negative estimates in episodes HW10 (−1.09), HW11 (−1.18), HW12 (−0.80), HW15 (−0.88), and HW16 (−1.27), indicating the association with the variability in the LST ranges explored in this analysis. In consideration of all episodes, a predicted decrease in the relative probability of reaching the highest LST range was observed for areas TSQ and PIT compared to HVP areas. The result for TSQ areas (estimate: −1.68) showed higher explanatory strength and stronger significance than that for PIT areas (estimate: −0.88) for decreasing the relative probability of exceeding the highest threshold set within the LST ranges (above 41 °C) (Table 7).

Finally, the regressions performed between orientation as the independent variable and LST ranges as the dependent variable did not show statistical significance for any of the episodes or for all episodes combined (model fitting information sig. > 0.05 in all cases). Therefore, the results have not been included in this article.

4. Discussion

This study carried out an investigation into the variability of land surface temperature (LST) values during different heat wave (HW) episodes from 2017 to 2023 in the city of Granada. The analysis focused on target areas within the urban green infrastructure (UGI), specifically on smaller public urban green spaces (SPUGS), characterized by varying percentages of different compositional elements. To address the existing challenges in the interpretation of LST values and the relationship with the capability of UGI assets to mitigate heat stress derived from higher surface temperatures (Saaroni et al., 2018), the study considered spatio-temporal scales and thermal comfort aspects.

The observed trend in the intensity and duration of HW in our study area aligns with the findings of existing research in the Mediterranean region (Molina et al., 2020). Following the most intense HW episode (25 July to 2 August 2020), where 98.83% of areas recorded values above 39.01 °C, a slightly upward trend was observed thereafter. The last three episodes recorded in July 2022 and August 2023 registered LST values for all areas that fell into the upper ranges, surpassing the 39.01 °C threshold. (Figure 2, Table 3). In addition to the increased intensity, the affected area during HW tended to expand, consistent with similar findings in the Mediterranean region (Pereira et al., 2017). While most target areas recorded LST values below 39.01 °C in the initial episodes (2017–2019), more than 75% of the areas registered values above 37.01 °C from episodes in August 2020 onwards, reaching this proportion in over 96% of the last episodes during the years 2022 and 2023 (Table 3). Specifically, the average extent of HWs in the Iberian Peninsula is expected to range from 6% to 8% per decade in the near future (Lorenzo et al., 2021). This increasing trend in spatial extent of HWs under future climate conditions implies heightened human exposure among other associated effects such as ecological, natural risk, and energy impacts (Palipane and Grotjahn, 2018; Schoetter et al., 2015).

Regarding the statistical analysis of the relationship between reached LST ranges and composition elements, the ordinal regression models did not yield statistically significant results for episode HW8, the most intense one. Episode HW8, spanning from 25 July to 2 August 2020, presented the highest land surface temperature (LST) values during the study period. In comparison to the year 2023, the year 2020 had the highest average temperatures recorded in the months leading up August (Agencia Estatal de Meteorología - (AEMET), 2019). Exploring further the particularity of HW8, it is noteworthy to acknowledge that previous analyses conducted in the Mediterranean region underscored the significant role of variables predicting and influencing LST, especially solar radiation at the same geographical point and elevation (Zhao and Duan, 2020). Solar radiation, especially during the hours for which we retrieved data for this study, is affected not only by climate factors, such as temperature, relative humidity, wind direction, precipitation, wind speed, and cloud cover, but also by the presence of air pollutants (Nisha Nandhini. and Geethakarthi., 2021). In this context, considering the most intense heatwaves, HW8 (July 2020) and HW16 (August 2023), the air quality in July 2020, preceding HW8, was worse than that in August 2023, preceding HW16. Specifically, and for indicative purposes, 45.2% of days in July 2020 exhibited regular or poor air quality (based on the European Air Quality Index) ("European Air Quality Index," n.d.), whereas the percentage of days with regular or poor air quality was 29% in August 2023 ("Ayto.Granada: Calidad del aire," n.d.). This observation might suggest that air quality and pollution levels preceding a heat wave may exacerbate LST values. Furthermore, the role of smaller green spaces in their interactions with air quality becomes even more relevant (Hewitt et al., 2020; Matos et al., 2019). Additionally, it would be interesting to investigate if, under extreme heat conditions like those of this episode, thermal stress is so severe that only strategies like shading (Lin et al., 2010) or ventilation (Ng, 2009) prove to be the most effective in mitigating the impacts of warm spells.

However, the regression model based on the percentage of composition elements did provide significant information for the remaining episodes (Table 6). Vegetation composition elements, represented by the independent variables trees and shrubs, contributed significantly to explaining the avoidance of reaching the highest LST range. This highlights the effective role of trees and shrubs in mitigating extreme LST values (Lai et al., 2020). The observed capability of trees to decrease the logarithmic probability of reaching the highest LST range (above 41.01 °C) is particularly effective in Mediterranean regions (Chatzidimitriou and Yannas, 2015; Cohen et al., 2012); this is also the case for shrubs and other smaller-sized species (Marando et al., 2022), which showed a statistically significant capacity to decrease the log odds of reaching the highest LST range in our study, albeit in fewer episodes. This capacity reached its peak strength in the least intense episode (HW7), where trees and impervious surfaces showed significant results. This association of variables might, on occasion, generate this negative direction in the relative probability of reaching higher LST values (Karimi et al., 2020).

The presence of cobblestone, gravel, and pebbles (C/G/P) pavements as a composition element showed significant coefficients with a negative direction in episodes HW1, HW5, HW6, HW9, and HW15. The significance and directional relationship observed for the variable "C/G/P" in the model considering all episodes suggest that the presence of this type of surface might favor a decrease in the relative probability of falling within the LST range of maximum values, corresponding to the hottest one (above 41 °C), and could help counteract warming and the impact of hot extremes (Kappou et al., 2022; Seneviratne et al., 2018). Aggregates of light-colored C/G/P have intrinsic high albedo and emittance (Oke, 2002), which are key characteristics for maintaining lower surface temperatures when exposed to solar radiation and reducing surface and air temperatures (Noro and Lazzarin, 2015; Wu et al., 2021). In this study, this outcome aligns with findings obtained in the Mediterranean region, where highly reflective materials have demonstrated effectiveness in reducing surface temperature and mitigating the impacts of heat waves (Falasca et al., 2019). However, pavements of C/G/P may not be the most suitable in terms of usability, physical barrier management, and coverage guidelines of universal urban green area design (Piskin and Akdeniz, 2023; Wojnowska-Heciak et al., 2022).

The only composition element that presented a positive coefficient, and therefore a predicted increase in the log odds of reaching the highest LST range, was herbaceous species and grass in the HW11 episode (June 2022). According to the official regional environmental information network for the study area (Environmental Information Network of Andalusia—REDIAM), within the years under consideration in the study, 2022 in Granada exhibited, on the on hand, the highest vegetation water stress index (ratio between stressed and non-stressed vegetation) and, on the other hand, one of the lowest monthly average precipitations for the month of June (1.3 L/m2) ("Red de Información Ambiental de Andalucía - Portal Ambiental de Andalucía," n.d.). Herbaceous vegetation and grass can reach very high temperatures in the absence of evapotranspiration, and their positive impact on air temperature and, consequently, pedestrian heat stress, strongly rely on irrigation, so when this type of land cover becomes dry, the surface temperature can increase, negating its positive impact (Parison et al., 2020; Yang and Wang, 2015).

Composition elements, such as soil and buildings, both with the lowest average coverage percentages (Table 4), were found to be not significant predictors of LST variation. Specifically, concerning the soil composition element, the outcomes differed from potentially expected results, as dry and heat-stressed soil typically contributes to a positive feedback of increased air and surface temperatures (Benson and Dirmeyer, 2021; Stéfanon et al., 2014). Regarding buildings, the types found in the target areas are mainly kiosks or small maintenance infrastructures, and the lack of significance could be related to, besides their limited presence, the specific types of buildings identified, as low-height structures might not contribute significantly to heat stress (Salata et al., 2017). Similarly, pervious surfaces were also identified as not significant predictors of LST variation. In this case, the relatively low presence in the target areas might explain the lack of significance, as their effects become more noticeable when larger extensions are present (Mohammad Harmay and Choi, 2022) or in climates with milder temperatures than the Mediterranean region, featuring limited seasonal variations and more evenly distributed precipitation throughout the year (Hendel et al., 2018).

The identified area types resulting from clustering exhibit similarities with other studies that classify green infrastructure typologies based on impervious, pervious, and mixed pavements combining different vegetation types (trees, grass, and shrubs) with irrigated and non-irrigated surfaces (Bartesaghi-Koc et al., 2019), studies where urban green areas categories are based on usage (commercial, residential, or mixed-use) (Sabrin et al., 2021), or studies using local climate zones characterized by building typology and the amount of vegetated surface as drivers for heat-stress-related research (Geletič et al., 2016). However, the area types obtained after clustering in this study are more specific to the study area, which enhances the granularity and accuracy of the study, aligning it more closely with the actual conditions and features of the local UGI.

The regression models exploring the relationship between LST values, and the type of area defined after clustering demonstrated statistical significance (sig. model fitting information < 0.05) for all episodes (except HW1, HW7, and HW9) and for all episodes as a whole. Using areas defined as "Vegetated patches and public areas with scattered trees and shrubs, mainly occupied by herbaceous vegetation and grass" (HVP) as a reference, which exhibited higher average LST values (Figure 3), all other area types consistently performed better in terms of reducing the relative probability of reaching LST Range 5 (over 41 °C) (Table 7). Thus, this result could be interpreted as indicating a lower cooling effectiveness of the HVP areas. This may be attributed to their heavy reliance on substantial irrigation for herbaceous and grass covers, which is often challenging in climates like that of the study area, where soil water availability is frequently a limiting factor (Elbondira et al., 2021).

Consistent with previous research, among the technologies for reducing both air and surface temperatures and consequently improving outdoor thermal comfort, including cool pavements, greenery, solar control, shading, or spray systems, the combination of these technologies provides better outcomes than the use of technologies individually in terms of thermal comfort improvement (Bartesaghi-Koc et al., 2021). In particular, urban greenery, especially trees, as well as the combination of trees and hedges, have a high potential for mitigating heat stress. However, non-vegetated surfaces, such as reflective pavements, also have a cooling effect, and combined with greening strategies, the capacity to reduce the effect of extreme temperatures can be enhanced (Yenneti et al., 2020).

Notably, traditional squares and parks, characterized by semipermeable pavements made of cobblestones, gravel, or pebbles, along with the presence of trees and small scattered garden areas with shrubbery (TSQ), exhibited statistically significant associations with attained temperatures compared to HVP areas. The coefficients displayed by TSQ areas showed a consistently negative relationship in each HW episode (except HW1 and HW9) and when considering all episodes. This negative relationship suggests their potential capacity to decrease the relative probability of surpassing LST values of 41 °C. These areas feature surfaces composed of high-albedo reflective pavements with porous interstitial spaces, representing a structural coverage type that has a significant influence in reducing heat stress, at both surface and air levels, by increasing cooling effectiveness (Moretti et al., 2021; Santamouris, 2013). Furthermore, the stronger direction of the relationship observed for TSQ areas compared to areas with more vegetation, such as PPG areas, highlights how the cooling potential of urban trees may not be that high during warm spells, particularly in the Mediterranean region, where projected drying summers can potentially reduce vegetation benefits, making the influence of high-albedo materials, like C/G/P pavements, more relevant in this region (Schwaab et al., 2021). In this context, it is noteworthy that, while the regression model does not yield significant parameters in the variation of LST for individual composition elements during HW8 (the most intense episode) (Table 6), it does so for traditional square (TSQ) areas in that specific warm spell (Table 7). The distinctive behavior of TSQ areas, compared to others during this particular episode, could be attributed to two main factors. On the one hand, the presence of reflective pavements on urban ground surfaces has been demonstrated to significantly reduce surface temperatures and convective heat release into the surrounding air so they have can offer widespread cooling benefits (Schneider et al., 2023; Tsoka et al., 2020). On the other hand, for effective heat stress reduction, a combination of greenery strategies and the use of cool building materials, such as urban paving with heat-resistant designs, can contribute to the cooling capacity of urban settings during heat wave episodes (Hatvani-Kovacs et al., 2018). The synergistic integration of highly reflective materials with street trees, as observed in our study in TSQ areas, appears to be a highly effective approach for ambient air cooling and managing increased reflected solar radiation (Tsoka et al., 2018). Additionally, combining street trees with cool pavements is demonstrated to be an efficient method for preserving pedestrians' outdoor thermal comfort, particularly in the Mediterranean climate (Salata et al., 2017).

Compared to HVP areas, parks and garden areas mainly occupied by trees with hedge gardens (PPG) and pedestrian and transit areas with presence of trees and impervious pavements (PIT) showed similar results and were more likely to indicate a decrease in the relative probability of exceeding LST ranges over 41 °C from episode HW10 onwards (with an exception in episode HW12 for PPG). Regarding PPG areas, results of this study are consistent with previous research proving the capacity of vegetation in the Mediterranean dense urban matrix to mitigate the impacts of HW episodes' heat stress conditions (Iungman et al., 2023; Rosso et al., 2022; Salata et al., 2015). However, considering all episodes, only in PIT areas did the coefficients indicate a statistically significant negative direction in the log odds probability of surpassing 41 °C (LST range 5). Despite the capacity of PPG areas to ameliorate the impact of warm spells, mainly due to the presence of trees, they may not fully compensate for the effects of impervious surfaces in reducing LST. These effects can persist beyond the night hours (note that the retrieved Landsat images were acquired in the morning hours), and the determination of a location's LST and, consequently, its microclimate conditions, may not solely depend on the extent of tree cover but also on the presence of shade (Bartesaghi-Koc et al., 2022; Elbondira et al., 2021). Additionally, the presence of plastic-based impervious surface coatings (rubber and cast rubber) in PPG areas excessively increases LST values, generating extreme surface temperatures (Bozdogan Sert et al., 2021). Furthermore, the combination of pavements found in PIT areas, along with the inclusion of trees, can create highly effective conditions to alleviate the effects of episodes of extreme heat in certain urban geometries (Mohammad et al., 2021). These considerations would indicate the importance of planning new UGI areas and rethinking the designs of existing ones, to enhance well-being conditions during extreme heat episodes (Rey Gozalo et al., 2019). Furthermore, the significance of strategically placing vegetation in heat-exposed areas seems to be more effective in mitigating the impacts of HW than merely aiming for an increase in the percentage of green coverage (Zölch et al., 2016).

Finally, the regression models based on the orientation of the areas suggests that this variable is not a significant predictor in the variability of LST values during the recorded HW episodes, despite orientation being a condition that can potentially influence the impacts of warm spells due to its influence on the duration of shading periods and urban ventilation (Lai et al., 2019). The lack of significance in this study could be attributed to the fact that orientation tends to be more influential in linear geometries, such as street canyons or connectors between UGI patches (Karimi et al., 2022; Lam et al., 2021). It is indeed important to acknowledge certain limitations in this study. Firstly, ventilation and shade effects were not considered as independent variables in the regression models. The absence of these factors might introduce some level of incompleteness to the assessment, as both ventilation and shading can significantly influence local microclimates and subsequently impact LST values. Future studies could benefit from incorporating these variables to provide a more comprehensive understanding of the thermal dynamics in urban green spaces during HW episodes. Furthermore, there are additional variables that warrant further investigation for a more nuanced analysis. Among these, the typology and phenology of plant species emerge as crucial factors influencing their adaptability and resilience to present and future climatic conditions. A more detailed exploration of these aspects could contribute valuable insights into the effectiveness of different vegetation types in mitigating HW impacts throughout UGI areas in Mediterranean urban environments (Caneva et al., 2020; Langenheim et al., 2020; Morakinyo et al., 2020). Additionally, it is worth noting that nighttime conditions provide complementary information for a more exhaustive evaluation of the urban green spaces' cooling effects across the entire diurnal cycle. In subsequent research, examining the impact of external factors beyond UGI management, such as meteorological conditions (e.g., atmospheric circulation and cloudiness) and air quality, and considering urban planning and architecture for both existing and newly developed areas, could offer valuable insights into the influence on LST.

5. Conclusions

In conclusion, from the heat wave (HW) episodes analyzed since 2017, this study revealed how LST ranges increased across numerous areas, highlighting heightened thermal stress in a Mediterranean medium-sized compact city. Trees played a crucial role in lowering the log odds of reaching higher LST range (above 41 °C). Cobblestone, gravel, and pebble (C/G/P) pavements also showed potential in decreasing this probability. Herbaceous species and grass cover, however, exhibit a positive coefficient in one of the episodes, indicating higher relative probability of reaching higher surface temperatures. Orientation and certain composition elements, like soil and buildings, did not significantly influence LST variation.

Among area types, traditional squares and parks (TSQ), pocket parks and gardens (PPG), and pedestrian areas with trees and impervious surfaces (PIT) performed better than vegetated patches (HVP) in reducing the probability of exceeding LST Range 5 (above 41 °C). The study advocates for strategically placing vegetation in heat-exposed areas, coupled with pavements like C/G/P, as an alternative strategy to simply increasing green coverage. Therefore, UGI areas´ design, combining trees with reflective pavements, proved its potential effectiveness in mitigating HW impacts.

Future research should explore granular aspects like pavement types, shading, ventilation, and plant resilience to refine our understanding of these relationships at smaller spatial scales.

In summary, this study not only advances our understanding of LST dynamics during HW episodes, but also guides strategies for enhancing the resilience of urban green spaces during extreme heat events.

Author Contributions: Conceptualization, M.J.D.-C.; methodology, M.J.D.-C., P.C. and P.E.-C.; software, M.J.D.-C. and P.E.-C.; validation, M.J.D.-C. and P.C.; formal analysis, M.J.D.-C. and P.C.; investigation, M.J.D.-C.; resources, M.J.D.-C.; data curation, M.J.D.-C. and P.E.-C.; writing—original draft preparation, M.J.D.-C.; writing—review and editing, M.J.D.-C., P.C. and P.E.-C.; visualization, M.J.D.-C.; supervision, M.J.D.-C. and P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Grant C-EXP-167-UGR23 funded by Consejería de Universidad, Investigación e Innovación and by the ERDF Andalusian Program 2021–2027, and Grant PP2022-PP34 funded by Pre-Competitive Research Projects, University of Granada Plan Propio. Paloma Egea-Cariñanos is funded by Spanish Government under the predoctoral program FPU (FPU22/01819) funded by Ministry of Science, Innovation and Universities.

Data Availability Statement: Publicly available datasets were analyzed in this study. These data can be found here: https://www.usgs.gov/ (accessed on 10 October 2023); https://www.juntadeandalucia.es/ (accessed on 10 October 2023).

Acknowledgments: The authors would like to thank the Spanish National Geographic Institute and the Andalusian Environmental Information Network, Junta de Andalucía, and the U.S. Geological Survey for the spatial data and cartographic base provided for case of study.

Conflicts of Interest: The authors declare no conflicts of interest.

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CAPÍTULO 4. DISCUSIÓN GENERAL

En esta tesis doctoral se han identificado los distintos tipos de áreas verdes urbanas de la ciudad de Granada en función de su capacidad intrínseca para contribuir a la prestación de servicios ecosistémicos, los cuales son esenciales para la adaptación al cambio climático, la resiliencia urbana y la cohesión social en entornos urbanos (Jennings and Bamkole, 2019; Stoll et al., 2015). Se reconoce la importancia de estas áreas como una red verde funcional, capaz de integrar diferentes componentes del paisaje urbano en una estrategia unificada de mitigación y adaptación ambiental. A través del desarrollo e implementación de un protocolo estandarizado, escalable y transferible a otros entornos urbanos, se han logrado identificar con precisión las áreas de infraestructura verde urbana (UGI) combinando diversas fuentes de información, obteniendo como resultado un escenario que refleja de forma fiel y ajustada la geometría y realidad actual de la ciudad.

El enfoque principal de esta investigación ha sido evaluar cómo los espacios de la UGI pueden amortiguar de forma efectiva los impactos de las olas de calor (HW, por sus siglas en inglés), un fenómeno de creciente preocupación debido a su frecuencia y severidad, especialmente en la región mediterránea (Hidalgo García et al., 2022; Luterbacher et al., 2006; Rodríguez-Gómez et al., 2022). En particular, se ha llevado a cabo un análisis detallado sobre la capacidad de diferentes tipos de espacios verdes urbanos para amortiguar el estrés térmico durante estos episodios de temperaturas extremas. Los resultados indican que, especialmente, los pequeños espacios verdes públicos urbanos juegan un rol crucial en este sentido, registrando en el periodo de estudio las temperaturas medias más bajas y presentando las correlaciones negativas significativas más acusadas entre la temperatura superficial del suelo (LST) y el índice de vegetación de diferencia normalizada (NDVI). En suma, los resultados concretos sobre los SPUGS alumbran cómo los componentes de superficie y la tipología de estos puede influir en la regulación térmica urbana, proporcionando una base sólida para futuras investigaciones y aplicaciones prácticas en la planificación urbana sostenible y la gestión de la infraestructura verde en ciudades compactas de la región mediterránea.

Este estudio introduce una perspectiva holística, integral e innovadora en la disciplina de la planificación de espacios verdes urbanos, considerados como soluciones basadas en la naturaleza para la adaptación y mitigación de los impactos derivados del cambio climático. Propone la estandarización en la categorización de los activos existentes de la UGI, clasificándolos funcionalmente en núcleos (Core), nodos (Node), elementos de enlace (Links) y áreas de menor tamaño definidas como "Other" (SPUGS, por sus siglas en inglés *Small Public Urban Green Spaces*). Este protocolo no solo facilita la identificación precisa de las áreas de UGI existentes, sino que también proporciona una metodología reproducible y escalable para la incorporación de futuros desarrollos de infraestructura verde en la planificación urbana. La capacidad de unir diferentes fuentes de información para obtener un mapa más preciso de la UGI mejora la comprensión de su distribución y extensión, y al mismo tiempo facilita la identificación de zonas de la ciudad demandantes de este tipo de infraestructura con objeto de maximizar su contribución en la mejora de la resiliencia urbana y la adaptación a fenómenos extremos asociados al cambio climático. El esquema propuesto es consistente con las consideraciones y secciones afines del documento de referencia en esta materia a nivel nacional, la Guía de la Infraestructura verde Municipal (Calaza Martínez, 2019). Además de recoger las pautas descritas en esta guía, el protocolo resultante de esta investigación complementa y extiende sus recomendaciones, establece un proceso de implementación de la UGI secuencial, accesible y manejable, manteniendo un equilibrio ajustado entre lo sintético, funcional y efectivo, facilitando una implementación directa y especialmente en contextos donde los recursos o la experiencia técnica pueden ser limitados.

El modelo diseñado para la implementación de la UGI simplifica y agiliza el proceso de identificación de zonas activas en términos de provisión de servicios ecosistémicos y el análisis de su distribución, así como la evaluación preliminar de métricas como la accesibilidad y disponibilidad de áreas verdes en entornos urbanos. En este sentido, se reconocen sectores urbanos con deficiencias de superficie verde, siendo generalizada la demanda en todo el contexto local. Conforme a la localización en el entorno urbano, la distribución espacial de las áreas de la UGI identificadas reveló que los núcleos se encuentran principalmente en el sector Este de la ciudad, mientras que la mayoría de los nodos se localizan en la zona Oeste. Esta distribución espacial abriría la posibilidad de una planificación estratégica que busque proporcionar continuidad entre todos estos centros funcionales, consolidando un cinturón verde en la periferia urbana. Sin embargo, la implementación del protocolo también mostró la complejidad de aprovechar este potencial de continuidad ya que los enlaces identificados apenas conectan este tipo de áreas verdes (núcleos y/o nodos) entre sí, atravesando y/o conectando en muy pocos casos los centros funcionales de menor tamaño (SPUGS) dentro de la matriz urbana.

El escenario propuesto ofrece una disponibilidad de área verde de 32.1 m^2 por habitante, incluyendo el espacio verde periurbano de mayor extensión, la Dehesa del Generalife, y 15.9 m^2 al excluir esta área protegida, considerando su exclusión debido a su mayor distancia de la ciudad en comparación con otras zonas. A nivel nacional y en el momento en el que se implementó el protocolo por primera vez, este promedio se situaba en los 12.5 m^2 por habitante, lo que hizo que el esquema propuesto supusiera un buen primer paso para el desafío de proporcionar una mayor superficie de área verde urbana por habitante. Es crucial entender que el aumento promedio de superficie verde obtenido tras implementar el protocolo no implicaría una reducción de la infraestructura gris. De hecho, el desarrollo urbano intensivo actual, particularmente evidente en áreas mediterráneas, conlleva la desaparición de espacios verdes urbanos existentes (Hortas-Rico, 2014). Los resultados obtenidos sobre la evaluación de disponibilidad, actualizados a marzo de 2024, están en línea con los resultados obtenidos en la fase inicial de esta investigación (2018), aportando consistencia a este fenómeno. En la actualidad, se observan hasta 17 barrios donde el promedio de superficie verde por habitante no llega a alcanzar el mínimo de 9 m^2 recomendado por la Organización Mundial de la Salud. Esta carencia es especialmente crítica en ciudades del sur de la Unión Europea, donde la superficie promedio de áreas verdes urbanas por habitante es usualmente inferior a otras zonas de esta región (Kabisch et al., 2016). Como contrapunto, siete barrios periféricos superan con creces el promedio de área verde por habitante dentro del escenario menos restrictivo (32.1 m^2 / habitante, incluyendo la Dehesa del Generalife), aunque principalmente debido a su baja densidad poblacional. La evaluación inicial sobre la accesibilidad a zonas de la UGI, entendida como distancia directa o aérea, arrojó una interpretación de gran interés ya que el 67.2% del área urbana total contaba con acceso inmediato (menos de 100 m) a un espacio verde, el 97.7% se encontraba a menos de 300 m de cualquier elemento de UGI y casi el 100% de la extensión de la ciudad, tanto barrios céntricos como periféricos, estaría a 8 minutos a pie o menos de cualquier tipo de área de la UGI. Estos resultados encuentran su origen en el elevado número de las áreas definidas como "Other" o SPUGS (84.4% del total de áreas identificadas) y en su diseminación espacial, poniendo de relieve la importancia de este tipo de elementos de la UGI, y sugiriendo que la integración efectiva de esta tipología de espacio verde en la planificación urbana podría contribuir significativamente a optimizar la superficie funcional y activa en términos de aprovisionamiento de servicios ecosistémicos. En este sentido, investigaciones previas ponen de manifiesto como las SPUGS juegan un papel multifuncional y significativo en entornos urbanos complejos y densos, ya que pueden proporcionar cobijo y conectividad a reservas locales de biodiversidad, aumentar la resiliencia del ecosistema urbano, proteger a los ciudadanos contra episodios climáticos extremos o brindar servicios socioculturales (Koyanagi et al., 2012; Milliken, 2018; Niemelä et al., 2010). Incluso las SPUGS más pequeñas identificadas dentro de la UGI, tales como grupos de árboles y matorrales colocados en intersecciones de rutas peatonales, contribuyen a un acceso equitativo a espacios verdes y, en definitiva, a mejorar las condiciones de habitabilidad y sostenibilidad en la ciudad (Jim, 2013, 2004).

Es importante resaltar que la esencia de la UGI definida en este estudio, radica principalmente en la reconocida capacidad de las áreas verdes, entendidas como soluciones basadas la naturaleza, para el aprovisionamiento de servicios ecosistémicos de regulación, tales como la moderación del clima local, la mejora de la calidad del aire, la polinización o la prevención de inundaciones (Baró and Gómez-Baggethun, 2017; Marando et al., 2019; Millennium Ecosystem Assessment Program, 2005). En concreto, tras la implementación el protocolo, el análisis se centró en la regulación del clima local (regulación de la temperatura urbana) y la capacidad potencial de enfriamiento proporcionada por núcleos, enlaces y las áreas de menor tamaño definidas como "Other" (SPUGS). Para ello, se consideraron los episodios de olas de calor como fases de interés, dada la creciente prevalencia de este fenómeno en la ciudad debido al cambio climático, entre los años 2017 y 2023, lo que permitió la interpretación de los resultados para cada tipo de área durante estos eventos de estrés térmico. A diferencia de investigaciones similares que consideran el área urbana en su conjunto, el análisis realizado se centró en los espacios de UGI como unidades individuales, permitiendo así evaluar qué tipos de área podrían ofrecer una mayor capacidad de amortiguación frente a las altas temperaturas durante episodios de calor extremo a través del análisis de la LST, su correlación con el NDVI y su variación en función de los elementos de composición y tipología de área. En este punto, es importante destacar nuevamente que solo se registró un tipo de área núcleo dentro del límite urbano (Bosques de la Alhambra), por lo que los análisis estadísticos no incluyeron esta categoría, centrándose exclusivamente en los nodos, conectores y SPUGS.

Los resultados del análisis estadístico, orientados a evaluar la capacidad de enfriamiento de las áreas objetivo, mostraron coeficientes de correlación negativos entre los valores de NDVI y LST en todos los casos, evidenciando así su efectividad para amortiguar las altas temperaturas durante los episodios de olas de calor. El coeficiente de Spearman para todas las áreas, en cada evento, resultó ser estadísticamente significativo ($p < 0.01$), con correlaciones negativas más fuertes observadas durante los primeros 5 episodios, incluido el más cálido en 2020. Sin embargo, esta correlación se mostró más débil en los últimos 4 episodios. Este patrón podría sugerir que, aunque las áreas de la UGI continuaron desempeñando un papel relevante en la mitigación de las altas temperaturas, su efectividad pudo verse influenciada por un aumento en la intensidad y la frecuencia de las olas de calor.

En este contexto, el tipo de área nodo, que registró el promedio más bajo de valores mínimos de LST al considerar todos los episodios de olas de calor en conjunto, demostró una correlación negativa en todos los eventos, salvo en los dos últimos de 2022. Este resultado se asumió como esperado debido a la capacidad de los nodos, por definición, para proporcionar servicios ecosistémicos de regulación de una forma potencialmente más efectiva si se comparan con las áreas de enlace y las SPUGS. De hecho, los conectores y enlaces de la UGI registraron los promedios más altos LST, lo que podría ser debido a la gran heterogeneidad de elementos estructurales a lo largo de su característica distribución lineal, tales como asfalto, aceras y otras zonas pavimentadas carentes de vegetación. Además, no se encontró correlación entre NDVI y LST en las áreas definidas como enlaces en el episodio de ola de calor de 2021 y el primero de 2022, e incluso se observó una correlación positiva para el segundo episodio de 2020 y para el evento de más duración (18 días en julio de 2022) y segundo más caluroso dentro del periodo considerado en este análisis.

No obstante, atendiendo a la evolución de la LST por tipo de área se observó como las SPUGS mostraron los registros promedio más bajos por período. En suma, los resultados del análisis de correlación entre LST y NDVI para todos los episodios, combinados por tipo de área, mostraron correlaciones negativas más fuertes para las SPUGS en comparación con las áreas definidas como enlaces y, de forma inesperada, con los nodos (ya que se hubiera esperado una relación más fuerte entre NDVI y LST para espacios, a priori, más verdes). A pesar de las evidencias existentes sobre la alta capacidad de enfriamiento de parques urbanos de mayor tamaño (Aram et al., 2019), los espacios verdes urbanos más pequeños destacan por su capacidad para extender los efectos de enfriamiento a una distancia mayor que algunas áreas de mayor extensión, especialmente a nivel de micrositio (Gallay et al., 2023; Peng et al., 2021). Los resultados en este punto del estudio confirmarían como las SPUGS tendrían el potencial de reducir significativa y efectivamente la LST, no sólo en su propio espacio sino también en su entorno más inmediato, contribuyendo a la mejora del ambiente térmico de la ciudad, particularmente en matrices urbanas de alta densidad (Wu et al., 2021). Con estas bases, se abordó de forma exhaustiva una identificación detallada de los elementos de composición y tipos de SPUGS, con objeto de evaluar de forma más detallada qué actores contribuyen a potenciar esta capacidad de enfriamiento de la ciudad.

Respecto al análisis detallado sobre las SPUGS y su comportamiento ante la serie de episodios de olas de calor, se observó una tendencia ligeramente ascendente en la intensidad y duración de las olas de calor, mostrando consistencia con los patrones identificados en el arco mediterráneo (Molina et al., 2020). Tras el episodio más intenso registrado del 25 de julio al 2 de agosto de 2020, donde el 98.83% de las áreas registraron valores por encima de los 39.01 °C, se observó una tendencia ligeramente ascendente. Los últimos tres episodios, registrados en julio de 2022 y agosto de 2023, mostraron valores de LST para todas las áreas ubicados en los rangos superiores de LST, superando el umbral de los 39.01 °C. Además del aumento en la intensidad, la superficie afectada durante las olas de calor también mostró una tendencia ascendente, lo que concuerda con resultados análogos en el área mediterránea (Pereira et al., 2017). Mientras que la mayoría de las SPUGS registraron valores de LST por debajo de los 39.01 °C en los episodios iniciales (2017–2019), más del 75% de las áreas registraron valores por encima de los 37.01 °C a partir de los episodios de agosto de 2020 en adelante, alcanzando esta proporción más del 96% en los últimos episodios durante los años 2022 y 2023.

El análisis estadístico sobre las SPUGS se llevó a cabo mediante modelos de regresión ordinal, relacionando sus componentes de superficie, orientación y tipología de área con los valores de LST agrupados previamente por tramos. Esta recodificación de la temperatura superficial del suelo se realizó en consonancia con los umbrales indicativos del índice bioclimático PET ("*Physiological Equivalent Temperature*"), debido a su significativa correlación con la LST y la temperatura del aire, su aplicabilidad en entornos urbanos, su capacidad para considerar de manera detallada geometrías y superficies urbanas complejas, y su aplicabilidad en estudios que evalúan el impacto y la percepción de las olas de calor en las ciudades (Goldblatt et al., 2021; Gómez et al., 2013; Kalogeropoulos et al., 2022; Lai et al., 2019). En línea con investigaciones previas realizadas en la región mediterránea, se emplearon intervalos de 2ºC para establecer los rangos de LST, indicando un estrés térmico moderado (sensación térmica cálida) con registros por debajo de los 35°C, y un estrés térmico extremo (sensación térmica muy caliente) con temperaturas superiores a los 41°C (Cheung and Jim, 2017; Höppe, 1999; Potchter et al., 2018; Rodríguez-Algeciras et al., 2020; Salata et al., 2016). Esto permitió abordar de una manera efectiva la complejidad en la interpretación de los valores de LST y su relación detallada con la capacidad de las áreas verdes para mitigar el estrés térmico (Saaroni et al., 2018).

Es importante enfatizar que el enfoque en este punto del estudio se centra específicamente en comprender cómo los elementos de composición de los SPUGS o los tipos de estos espacios contribuyen a mitigar las altas temperaturas superficiales durante episodios de olas de calor. Se tiene en cuenta que factores circundantes pueden potenciar el estrés térmico e intensificar los impactos relacionados con otros fenómenos tales como el efecto isla de calor, pero abordar estos aspectos excede el ámbito del presente estudio, cuyo objetivo principal en este punto es adentrarse en las propiedades intrínsecas de los SPUGS dentro de la UGI. En concreto, los valores de emisividad utilizados en el cálculo de la LST están directamente relacionados con los elementos de composición dentro de cada espacio verde. El valor obtenido por píxel en cada área de la UGI se determinaría principalmente por la composición (sustancia, material, tipo de superficie, …) del píxel. Este enfoque permite evaluar la influencia de características específicas dentro de los SPUGS sobre la LST. De hecho, en situaciones donde la variación espacial de la LST es menos pronunciada, tal y como sucede en espacios de menor tamaño como son los SPUGS, y especialmente durante períodos de calor intenso, la influencia de elementos de configuración del paisaje urbano circundante (como la geometría o el nivel de aglomeración entre otros) no llegarían a tener tanta influencia explicativa en los valores de LST como los parámetros biofísicos o componentes de superficie de este tipo de espacio verde (Peng et al., 2018). Por lo tanto, se ha excluido intencionalmente un análisis profundo sobre cómo los factores adyacentes pueden modificar los valores de LST en un área de UGI específica. En términos generales, se explora cómo las características de los SPUGS pueden influir en las condiciones microclimáticas a una escala más amplia, en lugar de profundizar en cómo los factores circundantes exacerban los valores de LST para un área de UGI determinada. En definitiva, la esencia y el foco del estudio reside en cómo la gestión de áreas de UGI, especialmente de los SPUGS, puede potenciar la resiliencia contra los impactos derivados de las olas de calor en ciudades compactas de la región mediterránea.

Por un lado, los modelos de regresión ordinal aplicados revelaron el papel efectivo de los árboles y arbustos en la mitigación de los valores extremos de LST. La capacidad observada de vegetación en el área urbana para disminuir la probabilidad logarítmica de alcanzar el rango más alto de LST (por encima de 41.01 °C) mostró con las evidencias existentes en la efectividad de este tipo de coberturas en las ciudades mediterráneas (Chatzidimitriou and Yannas, 2015; Cohen et al., 2012; Lai et al., 2020; Marando et al., 2022). Por otro lado, la importancia y relación direccional observadas en el modelo para pavimentos semipermeables compuestos de distintos tipos de empedrado (materiales de alto albedo tales como guijarros, adoquines, cantos rodados o gravas) con espacios porosos intersticiales (variable "C/G/P"), considerando todos los episodios, sugirieron que la presencia de este tipo de superficie podría favorecer una disminución en la probabilidad relativa de caer dentro del rango de LST de valores máximos (por encima de los 41°C) y, por consiguiente, contrarrestar el sobrecalentamiento en superficie (Kappou et al., 2022; Seneviratne et al., 2018). Este efecto asociado al componente C/G/P es consistente con resultados obtenidos en otros núcleos urbanos de la región mediterránea, en los que la presencia de materiales similares de alto albedo demostraron su efectividad en reducir la temperatura de la superficie, atenuando así los impactos de las olas de calor (Falasca et al., 2019). Los elementos de composición, como el suelo desnudo y los edificios, ambos con los porcentajes de cobertura promedio más bajos, no resultaron ser predictores significativos de la variación de LST. En particular, en lo que respecta a la cobertura de suelo desnudo en las SPUGS, los resultados difirieron de lo que potencialmente se esperaba, ya que el suelo seco y estresado por el calor típicamente podría contribuir de forma muy significativa a una retroalimentación positiva de aumento de las temperaturas del aire y de la superficie (Benson and Dirmeyer, 2021; Stéfanon et al., 2014). Además, es importante destacar que atendiendo al efecto de los componentes de superficie en las variaciones de LST por episodio, no se encontró significancia estadística para ninguna de las variables en el evento más extremo del periodo considerado, del 25 de julio al 2 de agosto de 2020 (HW8). La ausencia de significancia estadística en este caso podría deberse a que los niveles de calidad del aire y contaminación previos a esta ola de calor podrían haber exacerbado los valores de LST, una casuística ya observada en contextos similares de la región mediterránea (Agencia Estatal de Meteorología - (AEMET), 2019; Zhao and Duan, 2020). En este sentido, el papel de los SPUGS en sus interacciones con la calidad del aire sería aún más relevante en términos de acondicionamiento del entorno urbano para afrontar los episodios de olas de calor (Hewitt et al., 2020; Matos et al., 2019). En este sentido, resultaría realmente útil investigar si, bajo condiciones de calor extremo como las de este episodio de 2020, el estrés térmico es tan severo que solo estrategias de ventilación (Ng, 2009) o protección solar mediante infraestructuras de sombreado (Lin et al., 2010) podrían ser las opciones más efectivas para mitigar los impactos de estos eventos extremos.

De forma aislada pero significativa, se detectó en algunos episodios una correlación positiva entre los valores de LST y NDVI, lo cual tendría mayor probabilidad de ocurrencia en todos los tipos de áreas de UGI en las ciudades del sur de la región europea, especialmente afectadas por un incremento del estrés hídrico y la escasez de agua (Ward et al., 2016). En este sentido, el único elemento de composición que presentó una significancia estadística como predictor de un aumento en la probabilidad logarítmica de alcanzar el rango más alto de LST fue la superficie ocupada por especies herbáceas y césped. Esta respuesta por parte de este tipo de cobertura vegetal encontraría consistencia con los resultados de los modelos de regresión que analizaron la influencia de los tipos de SPUGS en las variaciones de LST. Tomando como referencia los tipos de SPUGS con valores promedio de LST más altos, aquellas definidas como áreas públicas con árboles y arbustos dispersos, cuya cobertura está principalmente ocupada por vegetación herbácea y césped (HVP), todos los demás tipos mostraron de forma consistente en los modelos de regresión un mejor rendimiento en términos de reducir la probabilidad relativa de alcanzar un rango de LST por encima de los 41°C. De nuevo, esto puede atribuirse a las altas temperaturas que pueden alcanzar estas superficies vegetadas en ausencia de evapotranspiración y su alta demanda de irrigación, lo que supone un desafío en climas como el de la zona de estudio, donde la disponibilidad de agua en suelo y de regadío es frecuentemente un factor limitante (Elbondira et al., 2021; Parison et al., 2020; Yang and Wang, 2015). Por lo tanto, los resultados observados para las zonas HVP podrían tener un impacto directo en el aumento de la temperatura de superficie y, consecuentemente, en la temperatura del aire y el estrés térmico. De otro modo, esta respuesta podría señalar una eficacia reducida de las áreas HVP y de los elementos superficiales mencionados en la mitigación de los impactos de las olas de calor, sugiriendo que quizás no representen la opción más sostenible y efectiva desde el punto de vista de la planificación urbana, especialmente considerando el contexto climático actual.

De manera destacada, las plazas tradicionales y parques, con una característica presencia de pavimentos C/G/P, acompañados de árboles y pequeñas áreas dispersas de jardín arbustivo (TSQ), evidenciaron asociaciones estadísticamente más fuertes y significativas, mostrando coeficientes negativos que indicarían una mayor eficacia para reducir la probabilidad de alcanzar valores altos de LST. Esta efectividad no solo superó a las áreas HVP, sino también a otras zonas con composición arbórea similar, aunque con revestimientos superficiales impermeables, tales como áreas peatonales y de tránsito con árboles y pavimentos predominantemente impermeables (baldosas, asfalto y hormigón), definidas como áreas PIT. Este comportamiento de las áreas TSQ podría estar relacionado con el hecho de que este tipo de pavimentos de alto albedo con espacios intersticiales porosos, tienen una influencia significativa en la reducción del estrés térmico, tanto a nivel de superficie como de aire y que, combinados con estrategias de incorporación de cobertura vegetal de porte medio y alto, la capacidad para reducir el efecto de temperaturas extremas puede ser potenciada (Moretti et al., 2021; Santamouris, 2013; Yenneti et al., 2020). En suma, la relación observada en las áreas TSQ mostró una tendencia más marcada en los modelos de regresión, con coeficientes más negativos y significativos a través de prácticamente todos los episodios de olas de calor, así como en el análisis global de todos los eventos, en comparación con otras áreas con mayor presencia de vegetación, como parques y jardines principalmente ocupados por árboles con ajardinamientos de setos y arbustos, combinación de pavimentos impermeables y permeables, senderos peatonales o áreas de juego y deportivas (áreas PPG). Este resultado podría, deberse parcialmente a la presencia de pavimentos derivados del caucho, ampliamente usados en zonas lúdicas y actividad física, que incrementan de forma extremadamente excesiva los valores de LST en áreas PPG (Bozdogan Sert et al., 2021). No obstante, el mejor rendimiento observado para las áreas TSQ resalta cómo el potencial de enfriamiento asociado exclusivamente a la presencia de árboles y arbustos podría no ser tan alto durante los periodos estivales, especialmente en la región mediterránea, donde se anticipa que un régimen de precipitaciones significativamente escasas debilitaría los beneficios directos proporcionados por la vegetación, por lo que la influencia de materiales de alto albedo, como los pavimentos C/G/P presentes en las áreas TSQ, podría adquirir mayor relevancia en este contexto (Schwaab et al., 2021). Resultó de particular interés evaluar cómo mientras el modelo de regresión no arrojó parámetros significativos en la variación de LST para elementos de composición individuales durante el episodio más intenso (HW8), sí lo hizo para las áreas TSQ en ese evento en concreto. Esta observación respaldaría aún más la influencia de los pavimentos de alto albedo tipo C/G/P presentes en las áreas TSQ para reducir significativamente las temperaturas de superficie, la emisión de calor hacia el aire y en definitiva, el estrés térmico, ofreciendo así beneficios de enfriamiento particularmente beneficiosos en condiciones climáticas mediterráneas (Schneider et al., 2023; Tsoka et al., 2020).

Con todo ello, elevando el análisis a una perspectiva holística e integral sobre la discusión proporcionada respecto a la composición y tipología de SPUGS, se pondría de manifiesto que la combinación de elementos principalmente de porte arbóreo con superficies semipermeables y pavimentos con propiedades estructurales de mayor resistencia a altas temperaturas, reduce de forma efectiva el estrés térmico y potencia el efecto refrescante en los entornos urbanos, contribuyendo a atenuar significativamente el calor en contextos metropolitanos durante episodios de olas de calor. En particular, la integración de elementos característicos de las áreas TSQ en la estrategia de diseño y gestión de espacios verdes públicos, se presenta como un recurso efectivo para preservar el confort térmico en ambientes urbanos exteriores, particularmente en el contexto del clima mediterráneo (Salata et al., 2017). Se trata de una alternativa en la planificación de la UGI a explorar y promover, con el objetivo de mejorar la regulación de la temperatura urbana durante episodios de olas de calor (Hatvani-Kovacs et al., 2018). Al mismo tiempo, esta estrategia permite conservar y mantener algo tan valioso como el patrimonio estético histórico y característico que las ciudades de la región mediterránea encuentran en este tipo de áreas TSQ. En definitiva, este estudio pone de relieve que la clave para una intervención efectiva en los espacios verdes públicos de menor tamaño con objeto de optimizar su capacidad de amortiguación frente a altas temperaturas, radica en el uso y emplazamiento estratégico de la vegetación, complementado con criterios estructurales adicionales en el pavimento, resultando más beneficioso que simplemente gestionar la UGI mediante el reemplazo o aumento del porcentaje de cobertura verde, tanto para áreas existentes como para las de nueva creación (Zölch et al., 2016). Es importante destacar que, en este sentido, las investigaciones subsiguientes profundizarán específicamente en el papel de las diversas especies vegetales, tanto en la prestación de este servicio ecosistémico de regulación en particular como en la gestión y mitigación de ciertos diservicios (Carinanos et al., 2018; Cariñanos and Casares-Porcel, 2011).

Por último, como observación menor, aunque relevante, los modelos de regresión basados en la orientación de las SPUGS sugirieron que esta variable no sería un predictor significativo en la fluctuación de los valores de LST durante los episodios de olas de calor registrados en este tipo de áreas, a pesar de que la orientación es una variable que puede contribuir potencialmente en reducir el estrés térmico, debido su capacidad para generar espacios de sombra y favorecer la ventilación urbana (Lai et al., 2019). La falta de significancia en este sentido podría atribuirse al hecho de que la orientación tiende a ser más influyente en geometrías lineales, tales como las áreas urbanas de enlace que se identificaron en la UGI (Karimi et al., 2022; Lam et al., 2021).

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CAPÍTULO 5. LIMITACIONES Y PERSPECTIVAS PARA INVESTIGACIONES FUTURAS

El presente estudio presenta ciertas limitaciones identificadas como puentes hacia investigaciones futuras específicas, transversales y multidisciplinares orientadas a la planificación y gestión de la infraestructura verde urbana, con el objetivo de optimizar su contribución a la mejora del microclima urbano y, en última instancia, maximizar los beneficios derivados del aprovisionamiento de servicios ecosistémicos que proporcionan en entornos urbanos mediterráneos.

En relación a los aspectos puramente biológicos, variables adicionales que indudablemente merecen una investigación más profunda incluyen la tipología y fenología de las especies vegetales, aspectos cruciales para entender su adaptabilidad, resiliencia frente a las condiciones climáticas cambiantes actuales y su idoneidad para maximizar los efectos de atenuación del estrés térmico durante episodios de altas temperaturas (Caneva et al., 2020; Langenheim et al., 2020; Morakinyo et al., 2020). La selección de especies vegetales constituye un aspecto crucial, particularmente en el Mediterráneo, que debe ser cuidadosa y estratégica, priorizando especies que no solo cuenten con índices elevados de supervivencia, sino que prosperen bajo las condiciones proyectadas en la región, contribuyendo eficazmente a la mitigación del calor urbano. Es vital elegir especies con características específicas que se alineen con los objetivos de sostenibilidad y eficiencia hídrica, como aquellas que mantienen su follaje durante el verano para proporcionar sombra, presentan bajos requerimientos hídricos y demuestran una notable adaptabilidad a oscilaciones bruscas de temperatura. La importancia de esta selección radica no solo en la capacidad de las plantas para sobrevivir bajo estrés térmico sino también en su índice de plasticidad y potencial de aclimatación, garantizando así la sostenibilidad de los espacios verdes urbanos en el futuro (García-Plazaola et al., 2008). Investigar y promover el uso idóneo de especies adaptativas puede proporcionar una base sólida para el diseño de espacios verdes más resilientes y eficientes en el uso del agua, esenciales para enfrentar los desafíos climáticos en ambientes mediterráneos. Esta línea de investigación y aplicación práctica promete no solo optimizar el rendimiento de la UGI y mejorar la regulación térmica urbana sino también enriquecer la biodiversidad y la funcionalidad ecológica, cultural y social de la UGI en la matriz urbana. Además, resulta esencial garantizar los beneficios de la vegetación que las áreas de UGI proporcionan mediante una gestión efectiva de los posibles diservicios ecosistémicos así como del coste que estos pueden originar (tales como la emisión de polen u otros compuestos orgánicos volátiles, la presencia de especies invasoras, impactos adversos en la salud o costes económicos asociados) (Cariñanos et al., 2017). El conjunto de los aspectos mencionados despliega un amplio y prometedor abanico de opciones para los trabajos futuros, más detallados y específicos en este contexto, que darán continuidad a esta tesis doctoral.

En relación con la selección de áreas, la inclusión exclusiva de áreas urbanas en la definición de UGI, dejando fuera otras clases de usos del suelo como las áreas rurales circundantes a la ciudad, destaca una oportunidad para explorar cómo estas zonas periurbanas pueden integrarse de manera estratégica en la planificación urbana. En nuestro caso de estudio, las áreas rurales periurbanas de la "Vega" de Granada, aunque no se incluyen en la UGI, complementan su funcionalidad contribuyendo de forma sustancial al aprovisionamiento de servicios ecosistémicos en el área urbana (Sirakaya et al., 2018).

Con respecto a los datos seleccionados, conviene destacar que limitar la recolección de información satelital a las horas diurnas omite el análisis de las condiciones nocturnas, lo que podría proporcionar una evaluación más completa del efecto de enfriamiento de los espacios verdes urbanos. Incorporar análisis nocturnos en futuros estudios podría mejorar significativamente la comprensión de la efectividad de la UGI durante ciclos diarios completos. En este contexto sobre los datos considerados, es necesario mencionar que factores externos a la gestión de la UGI, tales como la calidad del aire, la circulación atmosférica, la nubosidad y otros elementos meteorológicos, desempeñan un papel crítico en determinar la intensidad y duración de las olas de calor, así como la eficacia con la que las áreas verdes urbanas pueden contribuir a reducir los impactos asociados a las olas de calor. Se trata de un complejo entrelazado de factores que subraya la importancia de adoptar un enfoque integrado en la investigación futura, que no solo considere el diseño y manejo de la UGI, sino también cómo las interacciones entre la infraestructura verde y las dinámicas externas pueden optimizarse para mejorar la resiliencia urbana durante episodios de altas temperaturas.

En el contexto del diseño y estructura de las áreas verdes públicas, se reconoce que la influencia de las áreas de UGI en las condiciones microclimáticas podría no depender exclusivamente de los elementos de composición o del tipo de área, sino también de los efectos de ventilación y sombreado. Estos no se consideraron como variables independientes en los modelos de regresión, lo cual podría introducir cierto nivel de carencia en la evaluación. La integración de estos factores en estudios futuros podría ofrecer una herramienta de gran utilidad en las fases de planificación, diseño o reacondicionamiento de espacios verdes públicos. Además, se debe atender a los desafíos asociados al diseño, selección y gestión de componentes de las áreas de la UGI, desde la adaptabilidad a condiciones climáticas extremas hasta consideraciones sobre el impacto físico, aprovisionamiento potencial de "diservicios" ecosistémicos, percepción social de bienestar y accesibilidad (Cariñanos et al., 2020; Hayes et al., 2022; Jayasooriya et al., 2020; Kronenberg et al., 2020; Semeraro et al., 2021). Esto subraya la necesidad de un enfoque holístico y multidisciplinario (desde la planificación urbana y arquitectura hasta la ingeniería de materiales) en futuras investigaciones para avanzar la optimización de la infraestructura verde urbana en el contexto climático y social actuales.

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CAPÍTULO 6. CONCLUSIONES

Los resultados de esta tesis doctoral ofrecen un valioso aporte al conocimiento sobre la infraestructura verde urbana (UGI), específicamente en el contexto de las ciudades compactas y tamaño medio de la región mediterránea. En términos generales, este estudio ha permitido desarrollar satisfactoriamente una identificación precisa de la UGI y abordar una interpretación efectiva y elocuente sobre cómo diferentes tipos y componentes de áreas verdes pueden atenuar los efectos de las olas de calor. A continuación, se presentan las conclusiones clave derivadas de la investigación llevada a cabo:

- Se ha establecido un protocolo de identificación precisa de la UGI y el análisis de sus componentes y tipos de áreas que, por un lado, cubre la demanda de una herramienta estandarizada-, escalable y transferible que, no solo maximiza y categoriza la superficie efectiva de la UGI, sino que también permite evaluar inicialmente los patrones de disponibilidad y accesibilidad de áreas verdes. Este marco de trabajo ha revelado la importancia de las áreas clasificadas como "*Other*", también definidas como SPUGS ("*Small Public Urban Green Spaces*"), ya que juegan un papel crucial en la reducción de la fragmentación de la UGI y en el aumento de la usabilidad, disponibilidad y accesibilidad de los espacios verdes.
- Los resultados subrayan la capacidad de las SPUGS para amortiguar los impactos de las olas de calor, mostrando una fuerte correlación negativa entre el índice de área verde normalizada (NDVI) y la temperatura superficial del suelo (LST) durante estos eventos extremos. Esta capacidad de amortiguamiento resalta la necesidad de identificar la composición de los SPUGS y entender cómo sus componentes contribuyen a mejorar la capacidad de enfriamiento de la ciudad.
- En cuanto a los componentes específicos, los árboles han demostrado ser fundamentales para disminuir la probabilidad de alcanzar rangos de LST más elevados, mientras que pavimentos de alto albedo tales como guijarros, adoquines, cantos rodados o gravas (variable C/G/P) también muestran potencial para disminuir esta probabilidad. Sin embargo, ciertos tipos de cobertura vegetal, como superficies ocupadas por especies herbáceas y césped, pueden aumentar la probabilidad de alcanzar rangos de LST más elevados en condiciones de mayor estrés térmico.
- Entre los tipos de áreas, las plazas tradicionales y parques, caracterizados por sus pavimentos C/G/P, acompañados de árboles y pequeñas áreas dispersas de jardín arbustivo (TSQ), los parques pequeños y jardines (PPG), y las áreas peatonales con árboles y pavimentos principalmente impermeables (PIT) mostraron mayor capacidad para reducir la probabilidad de exceder valores de LST por encima de 41 °C, en comparación con zonas públicas principalmente ocupadas por vegetación herbácea o césped y presencia de árboles y arbustos dispersos (HVP). En todos los episodios de olas de calor considerados, las áreas TSQ evidenciaron asociaciones estadísticamente más fuertes y significativas, mostrando coeficientes negativos que indicarían una mayor eficacia para reducir la probabilidad de alcanzar valores altos de LST.
- La combinación de estrategias en la gestión consciente y estratégica del diseño urbano y los materiales de construcción, como el emplazamiento planificado de la vegetación junto con el uso de pavimentos semipermeables del tipo C/G/P, emerge como una solución eficaz para la mitigación de los impactos de las olas de calor, en lugar de limitar las iniciativas a aumentar la cobertura vegetal.

Este estudio subraya la necesidad de continuar la investigación en este campo, incorporando otras disciplinas relacionadas con aspectos biológicos, la calidad del aire y la circulación atmosférica, así como con especialidades relacionadas con la arquitectura, el diseño y la ingeniería de materiales. En particular, se delimita de forma ajustada un marco de trabajo para próximos análisis más específicos sobre la composición, selección y uso de especies vegetales adaptativas de las áreas de UGI que puedan proporcionar una base sólida para el diseño de espacios verdes más resilientes en entornos urbanos de la región mediterránea. Como conclusión general, la presente tesis doctoral resalta el valor agregado que las SPUGS pueden ofrecer. Principalmente, estas áreas destacan por su papel crucial en la provisión de servicios ecosistémicos de regulación, como es la gestión de la temperatura urbana y la mejora del confort térmico. Este estudio no solo consolida el conocimiento existente, sino que también proporciona perspectivas valiosas para avanzar en la gestión sostenible de los entornos urbanos, destacando la importancia de la infraestructura verde urbana como una herramienta efectiva para abordar los desafíos asociados al contexto climático actual y futuro.

"... y que los musgos se sigan mojando entre adoquines" Manu Delgado ("Martes", 2023)