



The ecosystem services supplied by urban green infrastructure depend on their naturalness, functionality and imperviousness

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Accepted: 14 September 2023 / Published online: 22 September 2023
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Abstract

Urban green infrastructure (UGI) can provide key ecosystem services (ES) for human well-being. For this purpose, it is critical to ascertain which characteristics regulate the provision of ES by UGI. In this study, eight ES (water supply, water regulation, waste regulation, nutrient regulation, soil formation, carbon sequestration, air temperature regulation and air humidity regulation) of thirty UGI sites of Zaragoza (Spain), were evaluated using proxy indicators derived from analyzed soil samples, and in-situ measured air temperature and humidity. A principal component analysis was performed to group different ES, and to study the dispersion of different types of UGI along the distinct ES. Additionally, relationships, between the evaluated ES and predictors; flatness, imperviousness, regularity, naturalness and functioning of the UGI sites were studied through linear and quadratic regressions. Large UGI sites such as riparian zones, meanders and natural forests showed relatively high values of ES in contrast with more artificial sites. Moreover, the study showed that water supply, water regulation, soil formation, carbon sequestration and air temperature regulation were significantly and positively related to ecological naturalness and functioning, while imperviousness was the main predictor explaining the reduction of five ES. Our findings provide evidence for the existence of important interactions between predictor variables and ES in UGI. It also showed that the provision of urban ES can be improved expanding the variety and type of green infrastructure sites, decreasing impervious area, and increasing the naturalness and functioning of UGI.

Keywords Ecosystem services · Urban green infrastructure · Imperviousness · Naturalness · Functioning

Introduction

There is an increasing interest on improving the green infrastructure of urban zones (UGI) because of the global urban sprawl which causes degradation and fragmentation

of natural ecosystems (McDonald et al. 2018; Behnisch et al. 2022), and the challenge ahead for urban zones to develop an operational network of green sites supplying benefits to their inhabitants (Hogan and Ojima 2008; Kabisch et al. 2015).

UGI refers to the integration of systems with natural components into the built environment. Both terrestrial (green) and aquatic (blue) ecosystems are included here, although UGI is more generally used to simplify. The variety of UGI sites ranges from parks and green roofs to trees, wetlands and other natural systems (Goddard et al. 2009). Due to their environmental, economic and social benefits, UGI is increasingly recognized as an integral part of sustainable urban planning and development (Grimm et al. 2008), and there is growing interest in integrating green infrastructure into urban environments as they can contribute to sustainable development and human welfare (Chatzimentor et al. 2020; Hanna and Comín 2021). These benefits are called ecosystem services (ES) which are necessary for the well-being of urban citizens (Reid et al. 2005b). ES are traditionally classified into regulating services (e.g, carbon sequestration)

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(Lal et al. 2013), provisioning services (e.g., food production) (Holt et al. 2016), supporting services (e.g., soil formation) (Dominati et al. 2010), and cultural services (e.g., educational values) (Daniel et al. 2012). Although regulating services are more complex, recent natural disasters and the negative impacts of climate change have brought them to the public's attention (Krkoška Lorencová et al. 2016). For instance, there is a growing interest in buffering heat waves through UGIs to mitigate the urban heat island effect (Kabisch et al. 2017; Marando et al. 2018).

A growing amount of scientific literature targeting ES evaluation have been produced as a result of the increased interest in UGI (Haase et al. 2014). The methods applied to assess ES differ for each type of service. For instance, cultural services are often based on surveys and interviews (Francis and Jensen 2017). However, regulating and supporting services depend on basic data obtained through field sampling or experimentally (Prudencio and Null 2018), whereas economic valuation is frequently adopted to evaluate provisioning ES (Wiafe 2016). Additionally, different types of contrasts are frequently used to compare ES delivery between UGI types (e.g., urban park versus natural forest), or between gradients (e.g., gradient of imperviousness, gradient of naturalness) (Veerkamp et al. 2021), or between different cities (Larondelle and Haase 2013).

A case-specific combination of different types of UGIs and features of their components can buffer the local effects of climate change (Baró et al. 2014) but also mitigate global ones through the uptake of greenhouse gases (Gómez-Villarino et al. 2021; Kabisch et al. 2017). Therefore, to fight against the negative impacts of climate crisis, especially in cities, policy makers and urban planners need to focus on climate regulation by the implementation of climate-smart policies to enhance regulating ES such as carbon sequestration (Campos et al. 2022). Accordingly, it is essential to quantify ES (especially regulating ES) and to study their relationships with structural and functional characteristics of UGI elements and sites (e.g., plant cover and soil erosion). An UGI site is composed of natural and artificial components. Machado (2004) proposed a naturalness index defined by how much of the total area of a site, is occupied by natural components. Hanna et al. (2023) added functioning (Fun), defined as how much of the total area is affected by natural dynamics preserving its hydro-geomorphological aspects and ecological processes, to naturalness (Nat), hence creating the Nat&Fun index. The latter study suggested that increasing Nat&Fun might increase ES delivery hence attempting to link ES delivery to natural components and functions of the UGI site.

ES supply should be systematically incorporated into urban planning and policy, to ensure sustainable development (Rall et al. 2015). A recent survey addressed to policy makers, researchers and stakeholders from 15 European

countries about the integration of the ES framework in European city planning showed the disagreement between policy makers and researchers with respect to the main obstructions to enhance or improve green urban areas design (European Commission. Joint Research Centre 2015). Researchers perceived a low public awareness and political interest, whereas policy makers and other stakeholders had a more optimistic point of view. All types of participants agree that the main obstacles to a better implementation of UGI are competing interest from the building sector and lack of financial means. This is paradigmatic since investing in UGI may often be economically advantageous (Elmqvist et al. 2015).

Then, there are many positive evidences to enhance the evaluation of ES provided by UGI as a tool for guiding urban planning in a sustainable way. In this study, we aim to: 1) quantify the contribution of different UGI types to the provision of key regulating (carbon sequestration and water, climate, waste and nutrient regulation), supporting (soil formation) and provisioning (water supply) ES; 2) identify the relationships between UGI elements and ES delivery; 3) and between each ES and gradients of structural variables (regularity, flatness, imperviousness, Nat&Fun) to test its usefulness as predictors or drivers of ES supply. We hypothesized that UGI supplies key ES in a medium-sized city, whose magnitude of delivery is positively related to a natural and functional structure and Nat&Fun index but negatively to regularity, flatness and imperviousness. Furthermore, we speculate that the UGI sites with the same characteristics (correspond to the same group) agglomerate together and could deliver the same ES and with similar magnitude. With this study we contribute to a better understanding of the influence of various structural components of UGI and their impact on the supply of multiple ES, which can help to develop more cost-effective strategies for a true integration of green infrastructures into the urban environment.

Methods

Study site

The research area corresponds to the city of Zaragoza located in the autonomous community of Aragon in NE Spain, which is a medium-size city (van den Berg et al. 2017), and has a population of 693,229 and a land area of 967 km² (Fig. 1).

The Zaragoza UGI is made up of natural, semi-natural, and man-made areas that include both terrestrial and aquatic ecosystems. Some of them are tiny locations in the most densely populated area of the city, but the majority of the relatively sizable green areas (river banks, forests, and meanders) are found in the peri-urban areas surrounding the city.

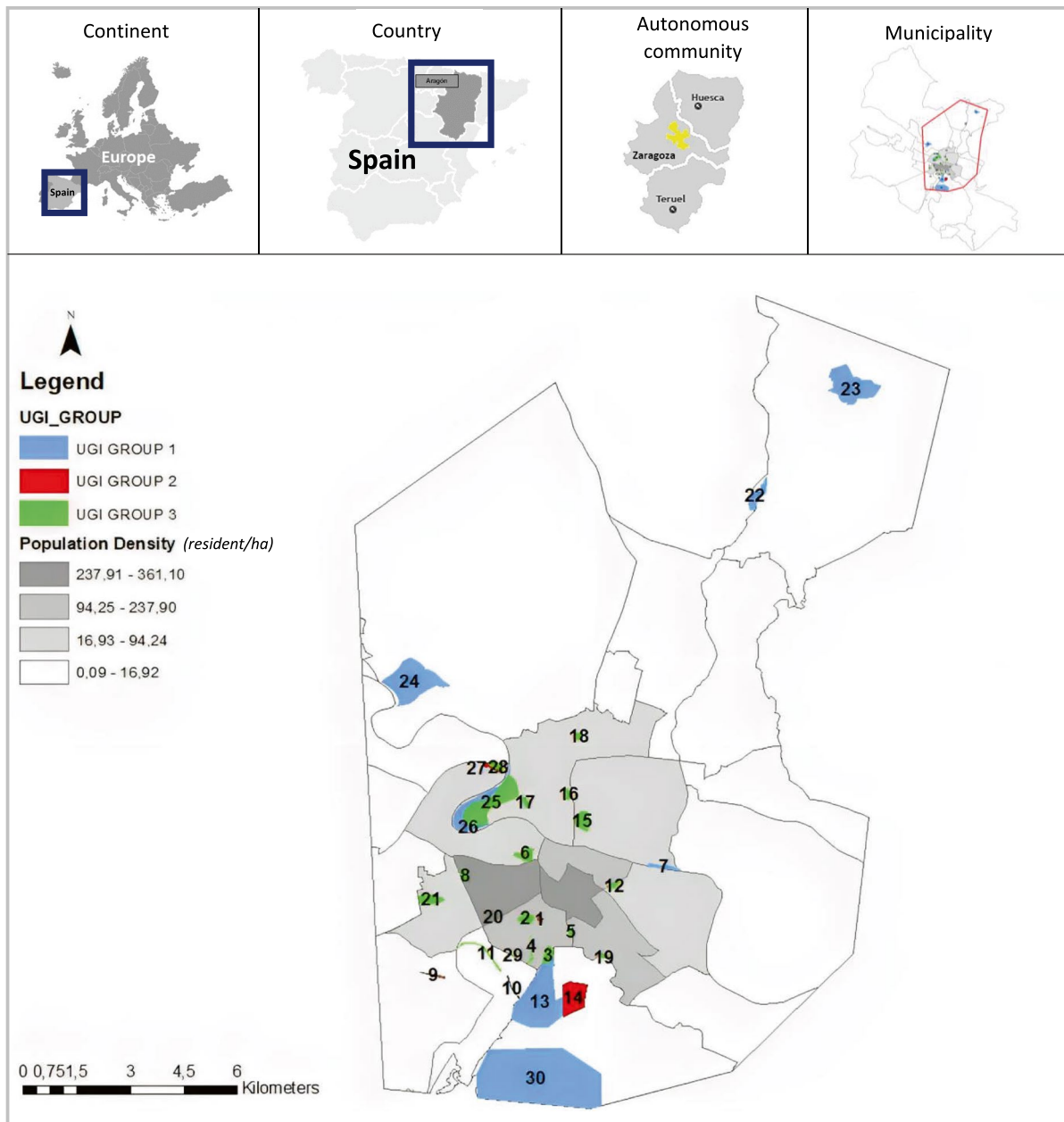


Fig. 1 Study area corresponding to the city of Zaragoza (Spain). This map shows the typology of the sampled UGI sites that we visited and sampled in relation with the population density of the city (inhabit-

ants/km²). (Check Table S1 for more details on the UGI sites and to which UGI group they belong)

In this study, 30 UGI sites representing the variety of UGI sites of Zaragoza were visited (Table S1) and data for the estimation of ES supply were taken (Fig. 1). These 30 sites covered proportionally a wide range of types of UGI sites (represented by the 89 sites studied in Hanna et al. 2023), and they showed a high data variability representing that range of types of sites. Thus, the number of UGI sites of each type was selected to look for a balanced proportion relative to the area occupied in Zaragoza city. Urban park was the predominant type of UGI in the city, being an important part of the complex urban ecosystem network providing

significant ES, so 13 out of the 30 sampled UGI sites corresponded to the category of urban parks. The other types sampled were canal, urban forest, river (2 units each category), cemetery, community garden, agricultural land, roundabout, square, street trees, university park (1 unit each one), located in the urban zone, and steppe, forest and meander located in the peri-urban zone.

In order to attribute ES values to different types of UGI and to test our hypothesis that UGI with similar characteristics could deliver the same magnitude and range of ES, we used the data of a previous study (Hanna et al. 2023),

in which 89 sites were ordered in a multidimensional space according to their shared socio-ecological features using a Principal Component Analysis (PCA), forming 3 groups/clusters of UGI sites with similar features. From the latter research, we selected 30 UGI sites (of the 89) to be sampled, and based on the PCA figure found in Hanna et al. (2023), these 30 sites were divided into 3 groups: UGI Group 1 incorporates rivers, meanders, urban forests, forests, an urban park and steppes, with relatively large areas, spontaneous vegetation developed naturally over undisturbed soils, and a high regulation by natural hydro-geomorphological factors; UGI Group 2 included street trees, square, artificial canal, cemetery, community garden, which are UGI sites characterized by artificial components and highly managed by human actions; UGI Group 3 consisted of urban parks, agricultural land, university parks, canal, and roundabout, which represent UGI sites located in flat areas with transplanted soil and vegetation characterized by regular plantations, but still with some degree of dependence on natural hydro-climatic factors.

Data collection and analysis

The first step was the selection of 8 regulating, supporting and provisioning ES to measure based on their ecological importance (Table 1). They include ES that have a significant impact on human well-being and urban sustainability (Reid et al. 2005a), and on a capital environmental crisis as climate change (Bartesaghi-Koc et al. 2018; Demuzere et al. 2014). Due to their importance in relation with global change and its strong relationship with human welfare (Mengist et al. 2020), 6 out of 8 ES are regulating services: water regulation, waste regulation, nutrient regulation, carbon sequestration, temperature and humidity regulation. The

other 2 ES corresponded to a provisioning (water supply) and a supporting (soil formation) service which are essential for human life and ecosystem functioning.

In each UGI site, 3 soil samples, separated 20–200m from each other, at a depth of 0–20 cm in the vegetated area were taken in each UGI site in order to assess water supply (WS), water regulation (WR), nutrient regulation (NR), soil formation (SF), carbon sequestration (CS) and waste regulation (WASTER) using proxy indicators based on Dominati et al. (2010, 2014) and Schaber et al. (2019). Assessing temperature regulation (MT) and humidity (MH) regulation was performed using data recorders (iButton®) that took hourly measurements during 1 month in the warmer period of the year (July–August 2022) to estimate daily air temperature and humidity oscillation. Thus, 6 data loggers covered with a double plastic cap (the lowest one leaky to let the air flow) were placed in each UGI site at 1.5–2.5 m height (3 data loggers were placed under the shade of trees, 3 exposed to the sun hanging from walls or statues but not over cemented areas), in locations not obstructed by objects, buildings or other structure that can distort the readings. MT and MH data were then upscaled to the whole UGI site according to the area (square-meters) occupied by vegetation in relation to the total area of the UGI site, to quantify the relative contribution of ES supply (ES/m²). Finally, these data were normalized for subsequent statistical analysis.

The second stage consisted of estimating the relative value of ES for each UGI group. For this, a radar chart was performed to identify the ES supply range and magnitude for each UGI Group. Thirdly, in order to test our hypothesis that UGI sites with the similar characteristics provide equivalent ES, a principal component analysis (PCA) was performed with the data of the 8 ES evaluated (Table S2). Therefore, PCA enabled to order the 30 UGI sites individually, and in

Table 1 Selected ecosystem services, abbreviations used in subsequent tables and figures, indicators used for their evaluation, units in which they were measured, and data source

ES Group	Ecosystem Service	ES abbrev	Indicator	Unit	Data source
Provisioning	Water Supply	WS	Soil water content	%	Soil analysis
Regulating	Water Regulation	WR	Inverse of soil bulk density	1:(g/cm ³)	Soil analysis
Regulating	Waste Regulation	WASTER	Conductivity	μS/cm	Soil analysis
Regulating	Nutrient Regulation	NR	Reactive phosphorus available to plants	mg/kg	Soil analysis
Supporting	Soil Formation	SF	Organic matter content	%	Soil analysis
Regulating	Carbon Sequestration	CS	Soil content of total organic carbon (TOC)	% of organic C per 100 g of soil	Soil analysis
Regulating	Meteorological Temperature Regulation	MT	Average daily difference of temperature range between data from data loggers in the sun and those in the shade	°C	i-Button recording
Regulating	Meteorological Humidity Regulation	MH	Average daily difference of humidity range between data from data loggers in the sun and those in the shade	% Relative humidity	i-Button recording

UGI groups, in a multidimensional space according to the type of ecosystem services they supply. Also, to fully comprehend the significance of these principal components and understand the underlying dynamics, it is crucial to investigate their correlations. Thus, we performed a correlation analysis on the resulting PCA components. The correlation value of these ES was calculated using the Spearman Method (Table 2).

Fourthly, we assessed ES delivery (Veerkamp et al. 2021), through studying their relationships with 4 characteristic features of UGI sites that are heavily involved in the design process and planning of UGI sites (Check Table S3 for details). Thus we compared ES supply along gradients of 1) naturalness and functioning (NatFun), calculated as the average value of the sum of the individual values of naturalness and functioning of each UGI site (Larondelle and Haase 2013, 2) green versus grey coverage (Imperviousness) estimated as the percentage of impervious surfaces relative to the total area of the UGI; 3) regularity, calculated as the percentage of the area occupied by regular and artificial forms relative to the total area of the UGI site. 4) flatness; leveling of the surface, estimated as the percentage of flat area relative to the total area of the UGI site. All these variables were used as predictor variables to provide information about the possible causes or factors that influence ES supply by UGI sites.

For this, individual regressions were performed to detect which variables were related to the supply of ES (Fig. 2). We tested the significance of simple and quadratic terms for each z-standardized (mean = 0, SD = 1) variable as well as the pairwise interaction terms to look for potential combined effects. Finally, we used the R package *glmulti* to automate model selection and identify the best-fitting model, based on the Akaike Information Criterion (AIC) and considering two-way interactions between all predictors (Calcagno and de Mazancourt 2010). Prior to this analysis, NatFun predictor was logarithmically transformed to reduce skewness, and all predictors were standardized to improve linearity against response variables

and ensure normal error distributions and homogenous variance. We also used the percentage of explained deviance to evaluate model performance. We visually checked homoscedasticity and normality of residuals.

Finally, based on the information we got from the data analysis, recommendation for the design, planning and management of the UGI site were given to face the challenges of climate change (Fig. 2).

Results

Highlighting ES supply for each UGI group

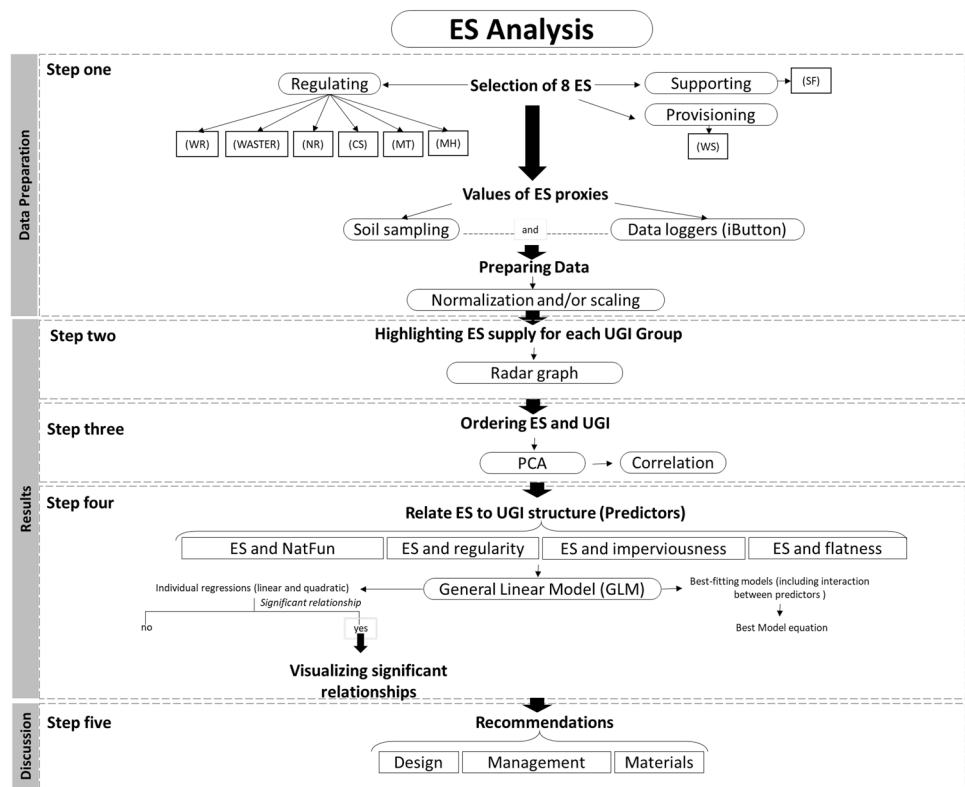
The distribution of ES values in the radar chart (Fig. 3) showed that the average (after standardization $\times 100$) relative values of ES obtained for each UGI group pointed to a low general provision of ES; i.e. all ES values were < 50 in the three groups (Fig. 3), which were particularly reduced for SF and WR. UGI Groups 1 and 2, which may have areas with dense and tall vegetation showed relatively high values of MT.

UGI Group 1 (river, meanders, urban forest, steppe, natural forest and an urban park) showed relatively high values of MT (48.53) and WS (34.9), followed by MH (31.7) and CS (18.46), but very low values of WASTER (9.73), NR (11.59), WR (5.84), and especially for SF (0.14). The highest values of UGI Group 2 (street trees, square, canal, cemetery, community garden) were found for MT (32.4), MH (22.12), followed by NR (18.23) and WS (14.36), whereas CS (9.37), WASTER (4.96), WR (1.75), and SF (0.08) displayed reduced or very reduced values in the case of the latter ES. UGI Group 3 (urban and university parks, roundabout, canal, agricultural land) showed relatively high values of MH (42.62), WS (28.2), NR (24.1), MT (21.37), CS (17.4) and WASTER (13.3), but very reduced values of WR (3.2) and SF (0.15).

Table 2 Correlation coefficients (* indicates significant correlations at $p < 0.05$) between 8 ES: Water Supply (WS), Water Regulation (WR), Waste Regulation (WASTER), Nutrient Regulation (NR), Carbon sequestration (CS), Soil Formation (SF), Temperature (MT) and Humidity Regulation (MH). Check the correlation matrix Fig. S2 in Supplementary materials

ES	WR	WASTER	NR	SF	CS	MT	MH
WS	0.6 *	0.28	0.17	0.4 *	0.47 *	0.21	0.24
WR		0.46 *	0.34	0.55 *	0.43 *	0.41 *	0.24
WASTER			0.24	0.43 *	0.45 *	0.09	0.32
NR				0.15	0.33	0.03	0.51 *
SF					0.81 *	0.26	0.13
CS						-0.03	0.3
MT							-0.07

Fig. 2 Methodology used for the assessment of ecosystem services (ES) and data analysis. Water Supply (WS), Water Regulation (WR), Waste Regulation (WASTER), Soil Formation (SF), Nutrient Regulation (NR), Carbon sequestration (CS), Temperature (MT) and Humidity Regulation (MH)

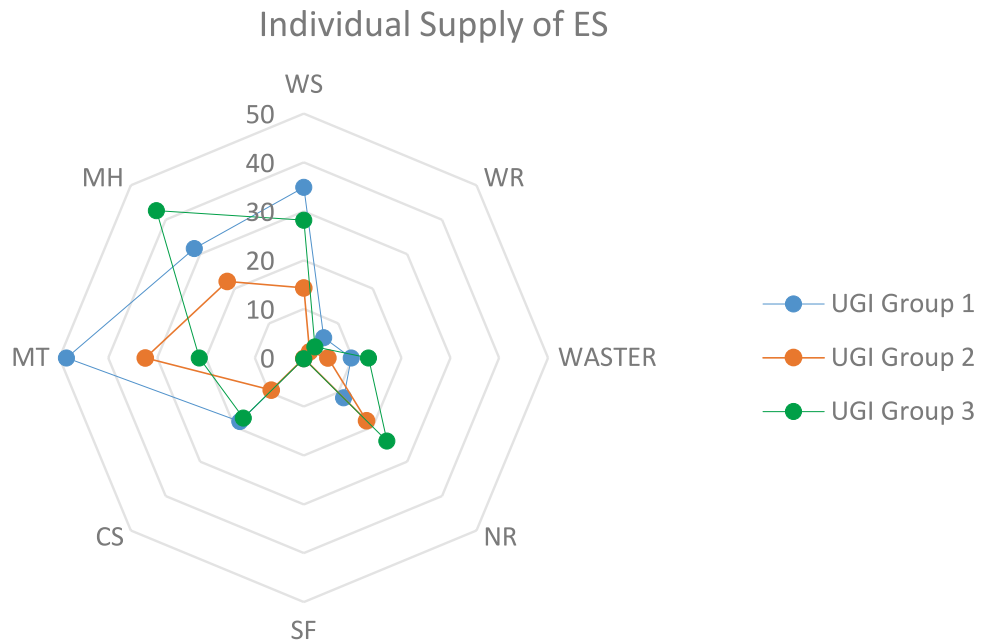


Ordering ES and UGI

The results of the PCA that were used to test our hypothesis that UGI sites with the same characteristics provide the same ES showed that the two first axes of the PCA analysis accumulated 51.3% of variation among UGI sites in relation to their supply of ES (PC1 = 29.9%; PC2 = 21.4%).

PC3 represented a smaller data variability (18.27%) and the ordination of variables was very similar to that of PC2. The rest of PCs represented a low data variability, less than 12% each one (Table S4). Accordingly, we retained the two principal axes since they represent most environmental variability and the main gradients in the sampled sites.

Fig. 3 Radar chart (spider net) graph of ES individual supply for each group of UGI elements. WR = Water Regulation, WS = Water Supply, WASTER = Waste Regulation, NR = Nutrient Regulation, CS = Carbon sequestration, MT = Temperature Regulation, MH = Humidity Regulation, SF = Soil Formation



PC1 represents the relative ES supply of UGI. PC1 was negatively correlated with all the ES assessed and represented a gradient from sites with a reduced ES supply on the right to sites with a greater magnitude of ES supply on the left (Fig. 4). For example, the point on the far right of axis 1 corresponded to the UGI site steppe, which displayed very low relative values of ES (No. 30 in Table S1). It represents a typical semiarid steppe: poor in nutrients and with a predominance of gypsum soils in the peri-urban zone of Zaragoza city (Fig. S1). The differences with other types of UGI sites in terms of landscape, soil features and fauna and flora, translated into a reduced and different ES

supply. On the far left of axis 1, two meanders with relatively high ES values are represented (No.22, No.24 in the peri-urban zone of Zaragoza), which are large natural areas that still maintain their hydro-geomorphological aspects.

PC2 correlated positively with 5 ES (NR, MH, MT, WS, WR) but negatively with 3 ES (WASTER, SF, CS). This contrasting pattern points to a trade-off between the ES more related with functional characteristics (NR, WR, WS, MH, MT) that support key ecological processes (soil nutrient removal, soil infiltration capacity, soil retention capacity, and buffering effects of the vegetation on humidity and temperature daily changes), and structural characteristics of the

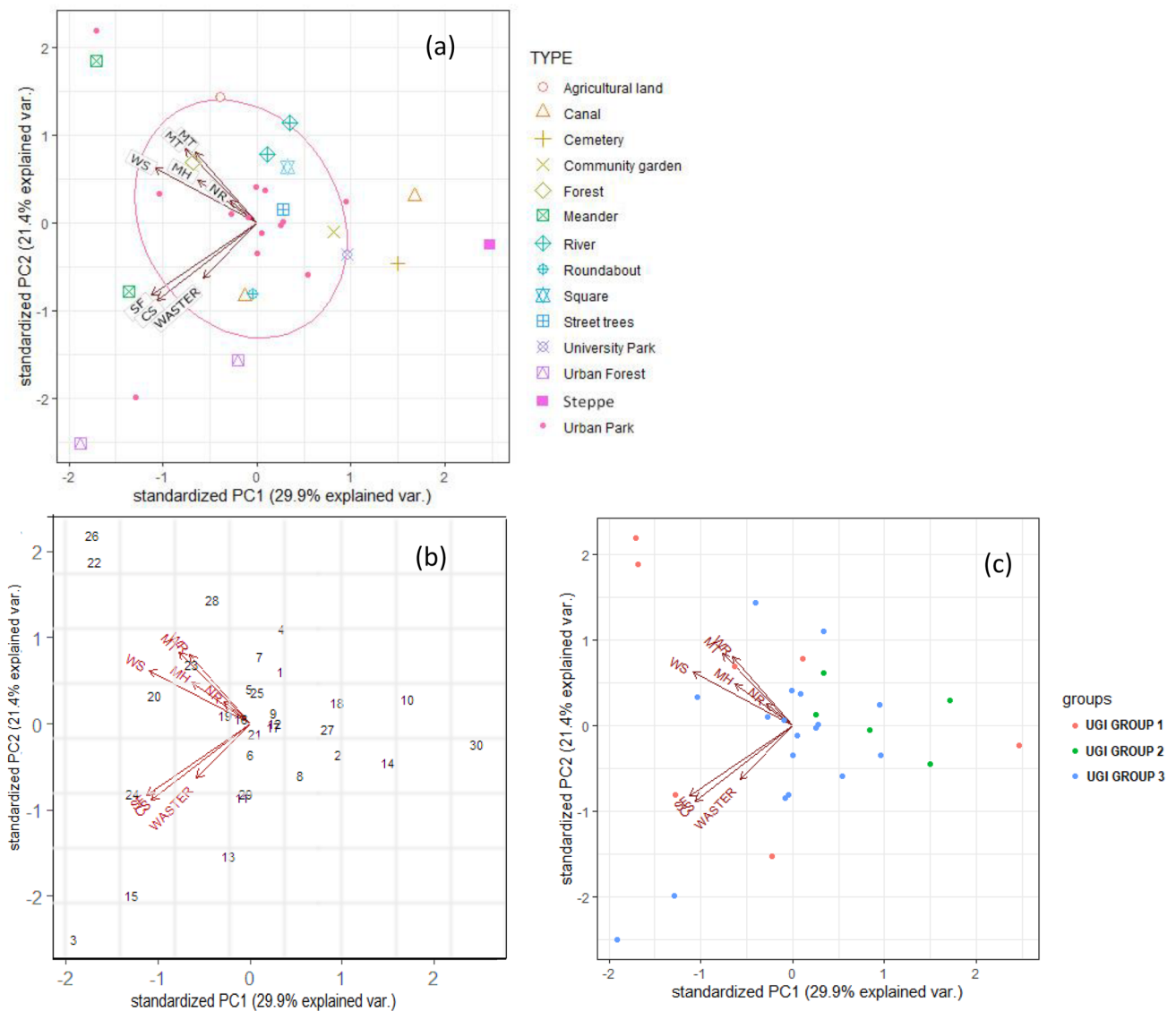


Fig. 4 **a** PCA ordination (using first two axes) of UGI sites according to their supply of ES; **b** each number represented a UGI site found in Table S1; **c** showed the distribution of different UGI sites corresponding to each UGI Group. Water Supply (WS). Water Regulation (WR), Waste Regulation (WASTER), Nutrient Regulation (NR), Carbon sequestration (CS), Soil Formation (SF), Temperature (MT) and Humidity Regulation (MH)

(WR), Waste Regulation (WASTER), Nutrient Regulation (NR), Carbon sequestration (CS), Soil Formation (SF), Temperature (MT) and Humidity Regulation (MH)

soil which are mainly related to the supply of SF, CS and WASTER. Accordingly, the most natural UGI sites (Nos. 26 and 22, two river meanders) characterized by a good conservation of their natural processes and dynamics were in the top end, while large UGI sites (Nos. 15 and 3, two large urban parks) which are managed artificially were in the most negative side of the PC2. These two UGIs (Nos. 26 and 22) were characterized by a combination of natural vegetated zones with long-time planted gardens, which could have impaired UGI functionality and its associated supply of key regulating ES as NR, WR, MH and MT. In summary, this distribution could indicate that the nature of the UGI sites (artificial or natural) was related with the supply of different types and magnitude of ES.

A mixture of different types of UGI sites is observed in the space defined by the two major principal components (Fig. 4a) which could reflect the variety of UGI sites and the variety of management and ecological conditions for similar UGI sites. The results also showed that sites belonging to UGI Group 3 were located in the center forming a cluster (Fig. 4a, c) with some exceptions (Parque Grande-Natural Zone No.3, and Parque Tio Jorge No. 15). Sites belonging to UGI Group 2 are located on the positive part of the PC1, which is the area representing reduced supply of ES, and some elements are in the cluster formed in majority by UGI Group 3 (Plaza San Francisco No.1, and street trees No.9). On the other hand, we observed a notable dispersion of the elements of sites belonging to UGI Group 1, which is composed of very different ecosystem types, inside the PCA graph.

Building upon the PCA results, the correlation analysis delved deeper into the interconnections between ES. Our results indicated that WS was significantly correlated with 3 ES; WR (correlation coefficient $r=0.6$), SF ($r=0.4$) and CS ($r=0.47$). In addition, we found that 4 other ES are significantly correlated with WR; WASTER ($r=0.46$), SF ($r=0.55$), CS ($r=0.43$) and MT ($r=0.41$). Furthermore, WASTER is also significantly correlated with two other ecosystem services: SF ($r=0.43$) and CS ($r=0.45$). NR is significantly correlated with one ecosystem service, MH ($r=0.51$). Finally, we observed a significant correlation between SF and CS ($r=0.81$), in addition to the correlations mentioned previously (Table 2).

Relate ES to UGI structure (predictors)

Individual regressions showed that WS, WR, SF, CS and MT were significantly and positively related to LogNatFun ($p < 0.05$ in all cases; Fig. 5; Table 3). However, they differed in the amount of explained variance (goodness of fit, R^2). LogNatFun was positively related to MT ($R^2=0.298$;

quadratic relationship), followed by WS ($R^2=0.209$; quadratic relationship), WR ($R^2=0.173$), and finally to SF and CS ($R^2=0.1$). Regarding significant quadratic relationships, convex and concave relationships were found between LogNatFun and MT and WS, respectively.

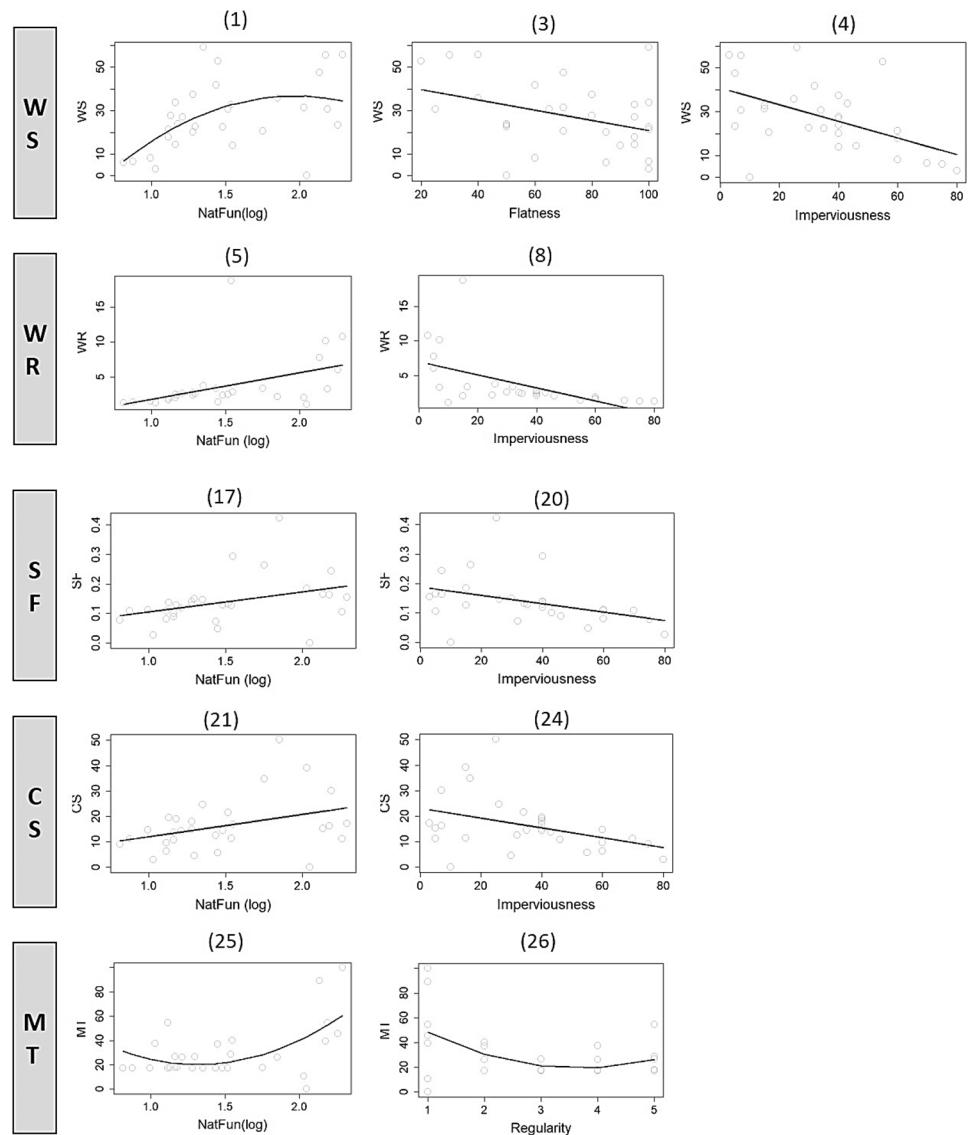
Imperviousness was the main predictor explaining reduced WR, WS, CS and SF ($p < 0.04$ in all cases). They also differed in the amount of explained variance. Imperviousness was strongly negatively related to WR ($R^2=0.27$), followed by WS ($R^2=0.243$), then SF ($R^2=0.143$), and finally CS ($R^2=0.123$). Therefore, compared to LogNatFun, Imperviousness showed a stronger relationship with all ES (except MT), especially with WR. We also detected a quadratic concave relationship between Regularity and MT, where Regularity was negatively related to MT ($p=0.016$, $R^2=0.2$). Finally, Flatness was negatively related to WS ($p=0.04$, $R^2=0.11$). Both have a minor individual influence on ES supply in comparison with Imperviousness and LogNatFun.

There was a negative interaction between LogNatFun and Imperviousness on WS (Fig. 6a). It seems that the negative effect of imperviousness was particularly acute when LogNatFun was reduced (Fig. 6a). Additionally, there was a negative interaction between LogNatFun and Imperviousness on WR. It seems that the negative effects of imperviousness on WR were more intense when occurring in relatively natural and functional UGIs (high LogNatFun value; Fig. 6b). The service MT was also modulated by several predictors' interactions. Thus, LogNatFun was positively associated to MT but only when imperviousness (Fig. 6c) or regularity (Fig. 6d) of the UGI site was low. Finally, imperviousness and regularity displayed a significant antagonistic interaction, i.e., although they had negative effects when acting in isolation, these impacts seem to be buffered when both predictors were high (Fig. 6e).

Discussion

In this paper we advance in the assessment of how different features and types of UGIs supply a different combination and magnitude of provisioning, supporting and, regulating ES, as well as the potential trade-offs and synergies between them (Dade et al. 2018). This study responded to the need for such comparison between different types of UGI sites (De Valck et al. 2019). In fact, to the best of our knowledge a comparative study assessing the same type of ES was lacking. In order to make informed decisions on the design and management of these ecosystems, it is essential to comprehend the relative advantages and disadvantages of

Fig. 5 Linear and quadratic regression plots showing significant (p -value < 0.05) relationships between predictors and WS (Water Supply), WR (Water Regulation), SF (Soil formation), CS (Carbon Sequestration) and MT (Temperature regulation)



the structural and functional features of UGI in providing multiple ES (Van Oijstaeijen et al. 2020), their drivers of change and the underlying mechanisms linking these drivers to ecosystem service outcome (Dade et al. 2018).

Assessing potential differences of ES provision between various types of UGI is crucial to effectively guide appropriate green infrastructure design and integrate green infrastructure into urban development strategies (Kain et al. 2016). Among the different ES evaluated, temperature regulation was the one which was supplied with greater magnitude by UGI Group 1 (river, meanders, urban forest, steppe, natural forest) and UGI Group 2 (street trees, square, canal, cemetery, community garden), whereas its supply in UGI Group 3 is much lower (Fig. 3). Cities act as heat islands due to the dominance of impervious surfaces, and lack of large

natural green spaces (Abdulateef and Al-Alwan 2022). There is a high social demand for temperature regulation through the investment in functional UGI (Akbari et al. 2016). The temperature regulation capacity of UGI has been studied extensively, and our results support the notion that UGI can significantly contribute to regulate temperature and mitigate urban heat island (Shao and Kim 2022). Hence, our study supports the significance of UGI in climate change mitigation and adaptation. According to our outcomes, the maintenance and construction of large functional UGIs dominated by natural processes, dynamics and structures, that display irregular shapes, permeable surfaces and undisturbed hydro-morphology can counteract the expected increase in urban temperature that can threaten the livability of urban areas in the short term as consequence of global warming (Ramyar

Table 3 Linear and quadratic regression summary of the 8 ES with 4 predictors. *P*-values (significant coefficients in bold type)

Indicator	Model	Variables	Std Error of the Estimate	Adjusted R Square	<i>p</i> -value	Equation of the model
WS	(1)	Log(NatFun)	50.59	0.209	0.0158	$-22.68\text{Log}(\text{NatFun})^2 + 88.99 \text{Log}(\text{NatFun}) - 50.47$
		$\text{Log}(\text{NatFun})^2$	15.72			
	(2)	Regularity	1.900	0.046	0.132	$-2.948\text{Regularity} + 36.71$
	(3)	Flatness	0.1105	0.110	0.040	$-0.236\text{Flatness} + 4.448$
WR	(4)	Imperviousness	0.1182	0.243	0.003	$-0.379\text{Imperviousness} + 40.827$
	(5)	Log(NatFun)	1.435	0.1735	0.012	$3.821\text{Log}(\text{NatFun}) - 2.054$
	(6)	Regularity	0.460	-0.0152	0.4582	$-0.34\text{Regularity} + 4.7$
	(7)	Flatness	0.0278	-0.025	0.594	$-0.014\text{Flatness} + 4.7$
WASTER	(8)	Imperviousness	0.027	0.2789	0.001	$-0.094\text{Imperviousness} + 6.96$
	(9)	Log(NatFun)	5.121	-0.025	0.595	$2.752\text{Log}(\text{NatFun}) + 7.028$
	(10)	Regularity	1.474	-0.015	0.465	$1.090\text{Regularity} + 7.71$
	(11)	Flatness	0.087	0.015	0.238	$-0.105\text{Flatness} + 18.665$
NR	(12)	Imperviousness	0.1006	0.030	0.177	$-0.139\text{Imperviousness} + 16.015$
	(13)	Log(NatFun)	8.038	-0.002	0.347	$-7.682\text{Log}(\text{NatFun}) + 31.679$
	(14)	Regularity	2.317	0.003	0.305	$2.417\text{Regularity} + 12.667$
	(15)	Flatness	0.1396	0.002	0.311	$0.143\text{Flatness} + 9.927$
SF	(16)	Imperviousness	0.164938	-0.035	0.992	$0.001\text{Imperviousness} + 20.182$
	(17)	Log(NatFun)	0.03259	0.103	0.045	$0.068\text{Log}(\text{NatFun}) + 0.037$
	(18)	Regularity	0.009658	0.058	0.104	$-0.0162\text{Regularity} + 0.189$
	(19)	Flatness	0.0006028	-0.011	0.422	$-0.0004\text{Flatness} + 0.173$
CS	(20)	Imperviousness	0.009658	0.143	0.039	$-0.001\text{Imperviousness} + 0.188$
	(21)	Log(NatFun)	4.292	0.1	0.048	$8.847\text{Log}(\text{NatFun}) + 3.177$
	(22)	Regularity	1.265	0.066	0.091	$-2.212\text{Regularity} + 23.279$
	(23)	Flatness	0.07888	-0.002	0.343	$-0.075\text{Flatness} + 21.791$
MT	(24)	Imperviousness	0.08557	0.123	0.032	$-0.192\text{Imperviousness} + 23.126$
	(25)	Log(NatFun)	64.88	0.298	0.003	$42.72\text{Log}(\text{NatFun})^2 - 112.42\text{Log}(\text{NatFun}) + 94.21$
		$\text{Log}(\text{NatFun})^2$	20.16			
	(26)	Regularity	12.934	0.206	0.016	$4.019\text{Regularity}^2 - 29.616\text{Regularity} + 73.845$
MH	(27)	Flatness	0.1595	-0.001	0.335	$-0.156\text{Flatness} + 40.755$
	(28)	Imperviousness	0.1770	0.083	0.066	$-0.338\text{Imperviousness} + 41.434$
	(29)	Log(NatFun)	8.762	-0.032	0.771	$-2.57\text{Log}(\text{NatFun}) + 40.491$
	(30)	Regularity	2.520	-0.021	0.534	$1.586\text{Regularity} + 31.695$
	(31)	Flatness	0.15265	-0.034	0.839	$0.031\text{Flatness} + 34.423$
	(32)	Imperviousness	0.17647	-0.027	0.633	$-0.085\text{Imperviousness} + 39.655$

and Zarghami 2017). However, other ES, such as waste regulation, carbon sequestration, soil formation, and water regulation, exhibited relatively low values across most UGI types. These results are in line with previous studies, which had also highlighted the big challenges in achieving optimal performance for ES in urban environments (Elmqvist et al. 2015; Sirakaya et al. 2018). For example, our investigation on the carbon sequestration ES aligns with the outcomes of previous studies focused solely on this ES that point to a small carbon sequestration efficiency of UGIs (Chen 2015; Kavehei et al. 2018). Although the positive impact of UGI on water regulation has been consistently observed

in previous research exploring the effects of UGI on water management (Dai et al. 2021), our relative low values could be due to urban parks within the city were the most studied type of UGI. Thus, this general low supply of ES could be caused by spatial restrictions within urban areas, leading to the establishment of smaller and fragmented green spaces, which can impact the overall capacity of UGI to provide essential ES, especially those that heavily depend on larger and interconnected natural sites, such as carbon sequestration and soil formation. Additionally, urban environments are prone to experience elevated pollution levels and intense human activities, affecting the ecosystem

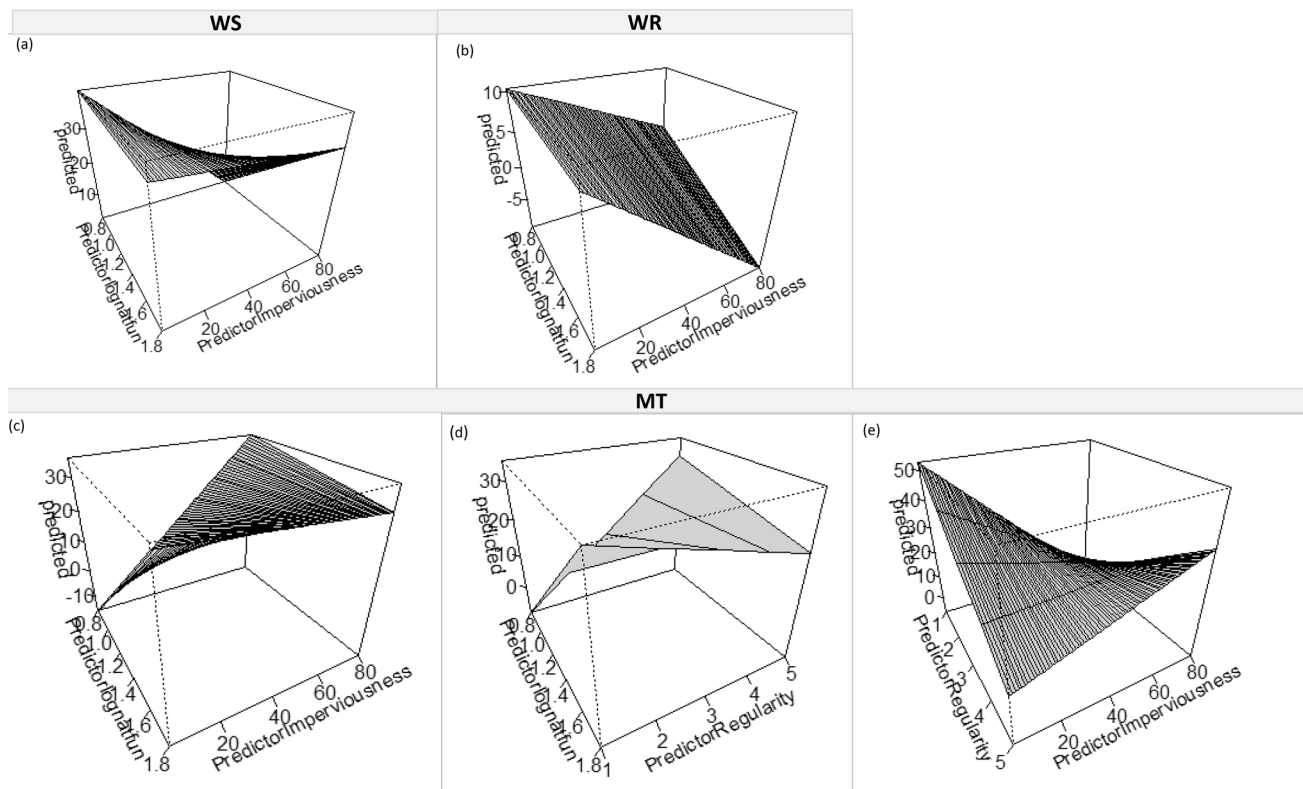


Fig. 6 a, b, c, d and e represent only the significant interaction ($p < 0.05$) perspective plots between dependent variables and predictors. The predicted variable represent the model equation of the

interaction $Z = a * X + b * Y + c * X * Y$ (a, b and c are coefficients). WS=Water Supply, WR=Water Regulation, MT=Temperature Regulation

processes responsible for waste regulation and water regulation (McDonnell et al. 1997). A potential solution could be to improve the 3D ecological connection among the UGIs of the city. Given the lack of availability of suitable spaces, green roofs and walls could contribute to provide this benefit (Mayrand and Clergeau 2018). Furthermore, urban planners must take in consideration the creation and design of rain gardens and bioswales that can improve water regulation in the city. These sites can be designed in small places and can be a smart tool for water and waste regulation (pollutant removal), and climate city adaptation (Kasprzyk et al. 2022).

This comes in agreement with our results, that suggested that the UGI of Zaragoza could increase the supply of ecosystem services through increasing the variety of types of UGI sites, through designing new UGI sites with higher naturalness and functioning characteristics and restoring existing sites as those found in UGI Group 1 (river, meanders, urban forest, steppe, natural forest), in order to buffer the negative undesired effects of global change. Sites that belongs to UGI Group 1 delivered the greatest range and magnitude of ES supply. Similarly, Mexia et al. (2018) evaluated multiple ecosystems inside a large park (44 ha) in Portugal. This study found that a forest inside the big park scored the highest on ES delivery due to its complex

natural vegetation. However, sites that belong to UGI Group 1 are large areas, and large free areas available to build UGI sites are scarce in cities, especially in the center and most populated areas. Hence the need to complement large natural and functional UGIs with smaller sites, that belong to UGI Group 2 (square, street trees, canal, community garden) and UGI Group 3 (urban parks, roundabouts, agricultural land, university parks). This should be done through increasing the Nat and Fun characteristics of small and artificial UGI sites inside the city, by expanding the vegetated area of UGI sites, also reducing imperviousness; and preserving or restoring their natural hydro-geomorphological features.

It could be also argued that there is a great dispersion and diversity of UGI types within the different UGI groups. This is true, because Zaragoza's UGI encompasses a diverse array of natural, semi-natural, and artificially constructed sites, spanning both terrestrial and aquatic ecosystems. It must be noted that the UGI typology used in this study, was developed by the European Commission, <https://biodiversity.europa.eu> based on (Cvejić et al. 2015). Given this high variability, we needed to categorize the UGI types into three UGI groups composed of UGI elements sharing similar structural characteristics, and to study and compare their ES provision. Thus, the principal components analysis

(PCA) (Fig. 3), revealed that UGI elements that belong to the same group (share similar characteristics) did agglomerate together, especially for UGI Group 2, and UGI Group 3. Their UGI sites share similar properties because the soil is mostly artificial so soil properties can be modified systematically (Valle et al. 2022). However, in the case of UGI Group 1, we found a notable data dispersion, which could be caused by the diverse nature of UGI sites (e.g.: No. 30 is a steppe and No. 24 is a meander), which greatly condition their soil properties.

NatFun and Imperviousness were the main predictors explaining higher and reduced ES delivery, respectively. For the composite index NatFun, which considers naturalness and functioning (Hanna et al. 2023), our results suggest that more natural and functional UGIs produced a greater range and magnitude of ES delivery, especially for water supply, water regulation, soil formation, carbon sequestration and temperature regulation (Fig. 5; Table 3). Accordingly, planners and landscape designers need to 1) increase the vegetated area of UGI sites, thus increasing naturalness, 2) also to preserve valuable natural remnants of biodiversity which are still driven by ecological processes (Van Oijstaeijen et al. 2020), and 3) finally to regard the newly constructed UGI as a potential useful tool for restoring urban degraded areas and recover (at least partially) the natural dynamics associated with hydro-geomorphological processes (Klaus and Kiehl 2021), hence increasing the functionality of the UGI elements and thus its ES delivery. This is in good agreement with the hypothesis stated in the end of a previous study (Hanna et al. 2023): NatFun affects the performance on UGI elements, through their impact on the potential supply of valuable ES. Regarding the significant negative relationship between Imperviousness and ES delivery imperviousness was the main predictor explaining reduced water regulation, water supply, carbon sequestration and soil formation. This finding agrees with previous studies about the effect of imperviousness on climate change, a key factor affecting water regulation (Salerno et al. 2018) and water supply (Caldwell et al. 2012) Also this study is in alignment with a previous study that stated that pervious vegetated area enhances carbon sequestration (Velasco et al. 2016). Furthermore, as expected, the present investigation showed that imperviousness decreased soil formation. Natural soil-forming processes are frequently interrupted as urbanization and land development increase impermeable surfaces such as roads, pavements, and buildings, resulting in negative consequences on soil quality and ecosystem health (Sauerwein 2011). Although in this study the relation between temperature regulation and imperviousness was not found significant, as it was in other studies (Morabito et al. 2021; Rajasekar and Hu 2011; Yuan and Bauer 2007), the results were very close to the significance value (p -value = 0.066). This could be due to the relatively reduced

number of sampled sites (30), but also that the mentioned studies used remote sensing and satellite imagery to study the relationship between urban heat island and imperviousness, whereas we used in-situ data collection through data loggers. Further research is needed, with more sample units and comparing the data of data loggers with those obtained by remote sensing. From a management perspective, restoration actions aiming to reduce impervious surfaces and the % of artificial soil in UGI element, would potentially enhance the supply of ES. However, if an artificial area (e.g., recreational area) is needed to provide cultural ES (Paracchini et al. 2014), then it would be advisable to design sustainable permeable pavement for the artificial areas interspersed with natural vegetated areas (Liu et al. 2018).

Finally, we found strong interrelationships between ES in the UGI. The study showed that water supply, soil formation, carbon sequestration, and temperature regulation are all significantly and positively correlated with water regulation. This suggests that water regulation is a key ES that can act as surrogate of several other ES. Similarly, waste regulation was found to be significantly correlated with soil formation and carbon sequestration (Table 2). These findings may provide insights into the underlying mechanisms that govern the supply of ES in UGI, as well as the ways in which they are interrelated to develop more effective strategies for conserving and restoring ES. However, our investigation could have benefited of an inclusion of a more holistic approach that also include the supply of cultural ES across UGIs (Amorim et al. 2021).

Beyond the individual effects of the predictor variables on the ES supply, we also provide evidence for interactive effects between predictors on ES. Water supply decreased as imperviousness increased, especially in UGI sites with low naturalness and functioning, as shown by individual regression coefficients and the significant interactions among predictors. Additionally, we found that the negative effects of imperviousness on water regulation were more pronounced in UGI sites with high NatFun values. These outcomes highlight the importance of designing UGI sites that are not only natural and functional but also consider the percentage of impervious surface to maximize water regulation. A recent flood event originated after heavy rains over a paved ravine and ring road of Zaragoza corroborates this issue (<https://hoyaragon.es/noticias-aragon/zaragoza/barranco-muerte-rambla-riada-zaragoza>). Furthermore, the positive relationship between NatFun and temperature regulation and the significant interactions found, suggest that natural and functional UGI may play an important role in regulating urban temperatures, particularly in sites with low imperviousness and regularity.

Only 4 UGI sites (13.3%) evaluated were located in the peri-urban areas, and we believe that by including more peri-urban green infrastructure sites, the study could have

provided even more valuable insights, especially if these sites are transitional zones between urban and rural areas, and can significantly help in climate change mitigation (Gómez-Villarino et al. 2021). Furthermore, we understand that the uneven sampling between urban and peri-urban areas may have resulted in the exclusion of key provisioning ecosystem services (Food production, raw materials production, energy production) as there are large areas surrounding Zaragoza city which could provide these services. In contrast, most UGI elements in densely populated neighborhoods are mostly designed and constructed with artificial components for recreational purposes. This arises the tradeoffs among ES supply, as artificial components are usually associated with impervious areas, reduced naturalness and dysfunctional UGI, and, consequently, with a diminished supply of ES.

Our work has showed that enhancing the naturalness and functionality of UGI is critical for providing a minimum range and magnitude of ES supply, confirming our hypothesis. In this way, we can ensure that urban green spaces continue to provide essential services that can mitigate the negative effects of climate change (Mathey et al. 2011), support human well-being (Lee et al. 2015), and contribute to a more sustainable and resilient urban environment (Marinelli et al. 2022). Also, the evidence from this study suggests that minimizing impervious surfaces can increase the UGI supply of ES. It could be argued that most UGI sites studied here corresponded to urban parks, at the expense of other UGI types. However, urban parks are the predominant type of UGI in a medium-city like Zaragoza (Hanna et al. 2023), because it is a source of rest, comfort and community fun in a stressful environment (Dunnett et al. 2002). Further research is needed that can englobe more UGI sites and types, especially private ones such as private allotments, backyards, and green roofs, often excluded from this kind of studies. Additional investigation can also encompass more provisioning (e.g., food production) and supporting ES (e.g., pollination), and introduce cultural ones (e.g., recreational and educational benefits), which should be addressed in relation to their drivers, as NatFun, Imperviousness, Flatness, Regularity and other potential predictors. Therefore, further analysis can include other predictors that are also involved in the design process and planning of UGI sites such as the number of plant strata, water availability and area (important for water management especially in urban areas), as well as biodiversity and connectivity between UGI elements. The challenge ahead is designing and implementing a mosaic of connected UGI sites and types combining the provision of all supporting, provisioning, regulating and cultural ES, which help to create a healthy urban environment while minimizing negative tradeoffs among ES.

Conclusion

In general, the UGI sites of a medium size city like Zaragoza provided low ES because of the lack of naturally vegetated zones (naturalness) maintained with hydro-geomorphological processes (functioning) in contrast with the dominance of impervious surfaces and artificial elements in most UGI sites. Beyond this general low provision, natural UGI elements such as river, meanders, urban forest, steppe, natural forest provided the highest temperature regulation, water supply, carbon sequestration, and water regulation. On the other hand, UGI sites such as urban and university parks, roundabout, canal, agricultural land provided the highest value of humidity regulation, nutrient regulation while waste regulation and soil formation were the lowest ES delivery across all UGI sites.

NatFun was significantly and positively associated with the delivery of 5 ES, but the percentage of impervious area was the main predictor explaining the decrease in 3 ES. Flatness and Regularity had minor but also significant negative effects on ES supply. Additionally, we found evidence for several synergistic and antagonistic interactions between predictor variables and ES in UGI.

In order to improve the delivery of ES, we propose to increase the variety of UGI sites and types, reducing the area of imperviousness and increasing (at least partially) their naturalness as well as their hydro-geomorphological processes and natural dynamics.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11252-023-01442-9>.

Acknowledgements The authors wish to acknowledge Dr. Mercedes Garcia and technicians at the laboratory of soil analysis in Pyrenean Institute of Ecology-CSIC in Zaragoza-Jaca (Spain) for their technical support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Author contribution E.H and F.C conceptualization; E.H, D.B and F.C methodology; E.H and F.C formal analysis; E.H, D.B and F.C investigation; F.C resources; E.H data curation; E.H and F.C writing—original draft preparation; E.H, D.B and F.C writing—review and editing; E.H visualization; F.C supervision.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Availability of data and material All data available upon request.

Declarations

Ethics approval All sites were sampled and surveyed with written permission from the municipality of Zaragoza in Spain.

Research involving humans and/or animals Not applicable.

Consent for publication All authors confirm submission to the Journal.

Conflicts of interest The authors report there are no competing interests to declare.

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