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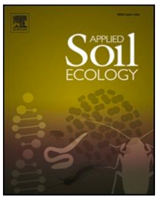

Review

Soil depth and vegetation type influence ecosystem functions in urban greenspaces

José Antonio Molina [a,*], Juan Pedro Martín-Sanz [b], Miguel Ángel Casermeiro [b], José Ramón Quintana [b]

[a] *Department of Biodiversity, Ecology and Evolution, Complutense University of Madrid, c/ José Antonio Novais 12, 28040 Madrid, Spain*
[b] *Department of Chemistry in Pharmaceutical Sciences, Complutense University of Madrid, plaza Ramón y Cajal s/n, 28040 Madrid, Spain*

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ABSTRACT

The contributions of soil and plant diversity to supporting ecosystem functions in urban greenspaces remains little known. Soil compaction and nutrient enrichment constitute major threats, and can give rise to the loss of ecosystem services in urban greenspaces. Our study focused on spontaneous vegetation in urban greenspaces in a Mediterranean city. We aimed to study the network correlations between the physical-chemical and biological properties of the soil at different depths along gradients of soil disturbance; and to analyse how vegetation and soil depth influence soil functioning. We focused our study on the following four spontaneous ruderal vegetation types: open vegetation on trampled soils, roadside vegetation, annual grasslands, and perennial forbs. They are widely distributed in Mediterranean urban greenspaces along soil compaction and nutrient enrichment gradients. We determined soil physical-chemical properties (organic matter, available nutrient content) and soil microbial activity relating to the main macro-nutrient cycles in the soil under each vegetation type at different soil depth (0–5, 5–20 cm). We used Spearman's bivariate correlations to study the relationships between soil variables at different soil depths by means of network analysis. We performed two-way ANOVAs to determine the influence of the plant-community type and soil depth on soil physical-chemical parameters and enzyme activity. We found that physical-chemical variables such as total organic carbon and bulk density represented the main drivers of soil functionality in the surface horizon (0–5 cm). Enzyme activity, however, associated with cycles of macro-nutrients such as arylamidase, arylsulfatase and phosphatase, had a greater influence on ecosystem functions in the subsurface horizon (5–20 cm). Regardless of the soil depth (0–5 cm, 5–20 cm), ANOVAs revealed a significant increase in bulk density between trampled soils (lowest values) and roadside vegetation (highest values); and in available phosphorus between annual grasslands (lowest scores) and perennial forbs (highest scores). Soils under annual grasslands and perennial forbs showed the greatest number of significant differences in soil between horizons. The highest number of significant differences were found between vegetation types in the surface soil horizon (0–5 cm) for soil organic matter and enzyme activities. This research therefore suggests that in urban Mediterranean greenspaces soil horizons are dissociated in terms of their soil parameter drivers, and that the surface horizon (0–5 cm) is more closely related to the response of the vegetation to soil disturbance gradients than the subsurface horizon (5–20 cm).

1. Introduction

Urban greenspaces (UGs) not only provide substantial ecological and social benefits in the form of ecosystem services such as biodiversity maintenance, climate warming mitigation and water regulation (Kim, 2016), but also have a positive effect on the wellbeing of urban populations (Bajirao, 2015). However, while the contribution of soil and biodiversity to supporting ecosystem functions is well known in natural ecosystems, it remains a young and growing field in urban greenspaces (Fan et al., 2023). It is particularly important to fill this gap in Mediterranean cities where climate change is expected to have an ever greater impact (IPCC, 2014), and where their capacity to adapt may be crucial (Faeth et al., 2011; Solecki and Marcotullio, 2013). Greenspaces in cities are subjected to major anthropogenic impacts that can interfere

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[*] Corresponding author at: Department of Biodiversity, Ecology and Evolution, Complutense University of Madrid, Spain.
E-mail address: jmabril@ucm.es (J.A. Molina).

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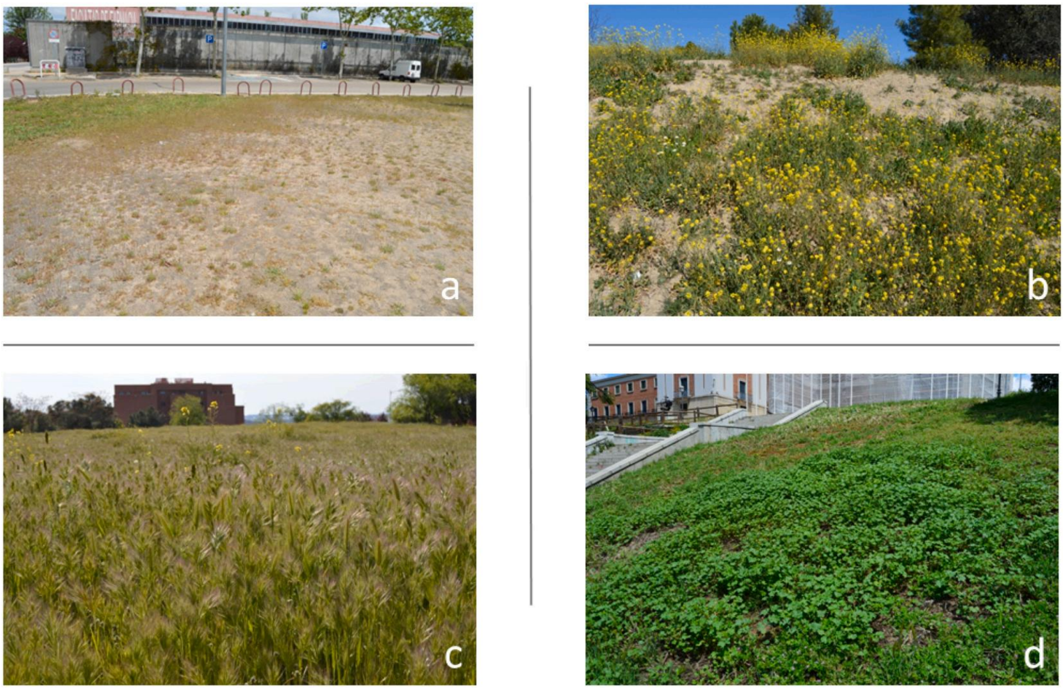

Fig. 1. Plant communities in the study: a) dwarf open vegetation on trampled soils characterised by *Plantago coronopus*; b) medium-size herbs with *Diplotaxis virgata* on slope roadsides; c) low-growing graminoid grasslands characterised by *Hordeum murinum* and *Bromus* species; d) medium-size herb vegetation with *Malva sylvestris*.

with their ecological functions. Urban processes involving earth moving and soil nutrient enrichment have impacts on soil physical and biochemical properties such as soil compaction and nitrogen and phosphorous cycling (Pouyat et al., 2007; Yang and Zhang, 2015; Lavy et al., 2016; Wang et al., 2017; Pouyat et al., 2020). Different soil conditions such as altered horizons or low organic matter content promote compaction, which impairs aggregates and limits the populations of organisms (Marcotullio et al., 2008). Urbanisation has also been associated with an increase in soil C mineralisation, N nitrification and P mineralisation rates, with the consequent increase in soil N content and P availability attributed to pollution from road traffic, dust, atmospheric depositions and anthropogenic waste deposits (Chen et al., 2010; Hu et al., 2011; Wan et al., 2020). Interestingly, urban soils are also subjected to a high input of dog faeces, which promotes soil fertilisation by means of phosphorous enrichment (Buchholz et al., 2021; De Frenne et al., 2022).

As considered here, urban ruderal vegetation (UV) comprises spontaneous plants not intentionally propagated by humans that are widely distributed throughout environments associated with urbanisation (Cervelli et al., 2013). Plant species characteristic of urbanised areas tend to follow a disturbance-tolerant, resource-acquisitive life strategy, compared to a more stress-tolerant and conservative strategy observed in plant species typical of non-urban areas (Petersen et al., 2021). UV species are increasingly important as vegetation cover in healthy UGs as they can tolerate soils with higher N, and often require little to no maintenance strategies (Del Tredici, 2010; Guo et al., 2018; Kalarus et al., 2019; Chocholoušková and Pyšek, 2003). UV types have been identified as good descriptors of urban habitats associated with anthropogenic disturbance gradients affecting soil organic matter content, soil compaction and nutrient cycling performance (Molina et al., 2023). They can also be considered as indicators of ecosystem services such as biodiversity maintenance, soil carbon storage and water regulation. Soils are arranged in a relatively predictable vertical structure (Chapin et al., 2002), although most of urban soils show the horizon arrangement disturbed, at least partially (Craul, 1999). Urban soils therefore exhibit great variation over short horizontal and vertical spatial scales (Simpson, 1996). Little is known of how vegetation types and soil depth are best related along gradients of soil disturbance.

Urban soils (US) include a complex of different soil types whose main characteristic is their genesis through human impact (Leguédois et al., 2016). US are mostly classified as Anthrosols or Technosols (FAO, 2015), and present anthropogenic diagnostic horizons together with other artificial artefacts (Wilding and Ahrens, 2002). Manmade US have specific physical characteristics in terms of bulk density and hydraulic conductivity, and their heterogeneous distribution can also be considered a characteristic feature of the urban soil profile (Prokof'eva et al., 2020). Urbanisation can significantly shape microbial community composition (Wang et al., 2017). US support highly homogenised microbial communities at the global scale with a high proportion of microbes associated to greenhouse gas emissions, faster nutrient cycling and intense abiotic stress (Delgado-Baquerizo et al., 2021). Since US are characterised by a strong horizontal and vertical heterogeneity (Greinert, 2015; Gómez-Brandón et al., 2022), detailed data are needed on the role of ecological functions at different soil horizons in different habitats.

The combined study of soils and biological communities is a promising area of research to obtain results for maintaining the sustainability of urban ecosystems (Bakhmatova et al., 2022). Ecological networks may effectively explain the impacts of disturbances on biotic and abiotic interactions (Ochoa-Hueso, 2016). Network analysis has been successfully used in the field of environmental research to study the relationships between selected soil biological and physical-chemical variables and ecosystem functions as affected by land use (Creamer et al., 2016; Martín-Sanz et al., 2022). Specifically, they have been employed to establish soil quality indexes in natural or agricultural environments (Andrews and Carroll, 2001; Martín-Sanz et al., 2022). However, this methodology has not yet been applied in urban environments despite the need for a greater understanding of urban soil processes (O'Riordan et al., 2021).

Ecological functions vary with the type of urban greenspace (Eldridge et al., 2021). In order to take this factor into account, we studied different habitat types within a single greenspace corresponding to a peri-urban university campus (Ciudad Universitaria) of 460 ha, located in the city of Madrid (Spain). Given the gap in our understanding of UV interactions with soils in urban environments, we wanted to test how disturbances such as soil compaction and nutrient enrichment affect soil functioning at different depths. To answer this question, we included four ruderal vegetation types, here considered as surrogates of habitats, that were previously recognised to be representative of Mediterranean cities and are related to soil compaction and nutrient enrichment gradients (Molina, 2022; Molina et al., 2023).

2. Material and methods

2.1. Study area

Our study was performed in the Ciudad Universitaria, a campus in the north-western peri-urban area of Madrid City shared by different universities (https://www.ucm.es/mapas-de-situacion-y-acceso). This campus comprises a set of buildings (faculties, research institutes and administrative centres), landscaped areas including green areas and green hedges, tree-lined walkways and lightly managed greenspaces. These latter greenspaces, where we focused our study, correspond in many cases to plantations with different species of pine trees where the spontaneous ruderal plants typical of the Mediterranean are the main vegetation cover. They are not irrigated but are given a light maintenance of annual soil clearing and two-yearly ploughing to prevent fires. These urban pine forests occupy a considerable extension in the peri-urban area of Madrid, and Ciudad Universitaria is one example. The study area has a Mediterranean climate, with a typical seasonal warmer and dryer period lasting from June to September, an annual average temperature of about 13 °C and annual precipitation of about 400 mm. Climate characteristics were obtained from Worldclim (for 1988–2018). The current soils in Ciudad Universitaria are classified as Anthrosols originally derived from Fluvisols and Cambisols (Quintana et al., 2022).

2.2. Sampling procedure

Four urban ruderal habitats were studied to collect habitat variety along soil compaction and soil nutrient availability gradients (Molina et al., 2023). The following is a brief description of the four vegetation types studied, mostly composed of annual plants (Fig. 1): a) dwarf open vegetation on trampled soils characterised by *Plantago coronopus*; b) medium-size herbs with *Diplotaxis virgata* on slope roadsides; c) low-growing graminoid grasslands characterised by *Hordeum murinum* and *Bromus* species; and d) medium-size herb vegetation with *Malva sylvestris*. Floristic composition and vegetation structure are shown in Molina et al. (2023). These types of communities are widespread in the peri-urban areas of Madrid. Soil was sampled within three squares (1m^2), randomly established in each vegetation type, hereafter designated trampled soils, roadsides, annual grasslands, and perennial forbs. A total of 12 plots were studied.

Soil samples were collected in April 2021 when all plant communities were developed. Soil water holding capacity (WHC) and bulk density (BD) were analysed in unaltered soil with cores measuring 5 cm in diameter in each site at two depths (0–5 cm and 5–20 cm). Sampling the soil at different depths provided reliable findings on vertical changes in soil conditions. Approximately 1 kg of soil was collected from each depth at each site and taken to the laboratory where it was fresh sieved with a 2 mm sifter to obtain the fine fraction in which the analysis was performed. This fraction was subdivided into two subsamples, one of which was refrigerated at 4 °C for subsequent use to determine enzyme activity and available nutrient content, and the other air-dried for physical-chemical analyses.

2.3. Soil analysis

We established 12 soil variables as surrogates of ecosystem functions under each vegetation type and at two different soil depths (surface horizon: 0–5 cm; subsurface horizon: 5–20 cm). Of these, 5 corresponded to soil physical-chemical properties and 7 to soil microbial activity relating to the main macro-nutrient cycles. The soil parameters related to water regulation that we analysed following ISRIC (2002) were soil water holding capacity and bulk density. Total organic carbon (TOC), as a proxy of carbon storage, was determined using the Walkley and Black (1934) wet oxidation procedure with potassium dichromate. As variables related to nutrient cycling, we studied the following two related to macronutrient availability: available phosphorus (AP) by extraction with sodium bicarbonate using the Olsen and Sommers (1982) method, and available ammonium (NH4-N) with potassium chloride following the Keeney and Nelson (1982) method.

Soil microbiome activity was determined from the enzyme activities related to the carbon, nitrogen, sulphur and phosphorus cycles. Specifically, the activities of β-glucosidase (b-GLU), phenoloxidase (PHE), dehydrogenase (DH), arylamidase (Aryl-N), urease (URE), phosphatase (PHOS) and arylsulfatase (Aryl-S) were determined using colorimetric substrates following ISO (2018); the exceptions were PHE which was examined following the DeForest (2009) method, and DH which followed the Schaefer (1963) method. The samples were first incubated in a MEMMERT IN 55 incubator, and a UV–visible spectrophotometer with a TECAN NANOQUANT INFINITE M200 PRO multi-well plate reader was used to determine all the activity measurements.

2.4. Statistical methods

Spearman's bivariate correlations ($P < 0.05$, SPSS v.28) were used to study the relationships between 12 soil variables at different soil depths (0-5 cm, 5-20 cm). Two undirected networks were generated based on Spearman correlations, one for each soil depth. In these networks the study variables are represented in the form of points called nodes, and the correlations between the variables in the form of lines called edges; the number of edges that join a pair of nodes is called distance. The analysis of the networks generated in this way makes it possible to study both the relationships between pairs of variables and also in relation to the total set of variables, providing a set of metrics that allow the comparison between networks (network metrics), and the importance of the variables within each network (node metrics). The following items will be studied in network metrics (Cherven, 2013): i) the number of nodes; that is, the number of variables that show at least one correlation; ii) the number of edges; that is, the number of correlations existing; iii) average degree, the average number of correlations of a variable; iv) weighted average degree, the average number of correlations of a variable, weighted by its correlation coefficient; v) diameter of the network, the maximum distance between two network variables; vi) density, the number of correlations existing out of the total possible; vii) modularity, a function that when maximised indicates whether the network variables form groups of variables or not; values of this function close to zero indicate that the nodes of the network form a single group (Newman and Girvan, 2004); viii) transitivity, the probability that two variables are correlated with a third; and ix) average path length, the mean distance between any two variables in the network. Regarding the node metrics, the degrees of each variable were studied to determine the most important variables, as measured by the number of correlations they have. The Gephi 0.9.2 software was used to determine the networks and the network and node metrics.

Two-way ANOVAs were performed to observe the influence of the plant-community type and soil depth on soil physical-chemical parameters and enzyme activity. An *a posteriori* Bonferroni test was then carried out to test the plant-community type in each soil depth and the soil depth in each plant-community type. The soil variables were normalised by converting them to logarithms. The assumptions of normality and of homogeneity of variances were met. Statistical analyses were done using SPSS v.28 software.

Table 1
Metrics of the networks generated from the Spearman's bivariate correlations ($P < 0.05$) between the soil variables at different depths (0-5 cm, 5-20 cm).

Network	Nodes	Edges	Average degree	Weighted average grade	Diameter	Density	Modularity	Transitivity	Average path length
0–5 cm	7	16	4.571	2.201	2	0.762	0	0.757	1.238
5–20 cm	9	18	4	3.094	3	0.5	0.097	0.76	1.639

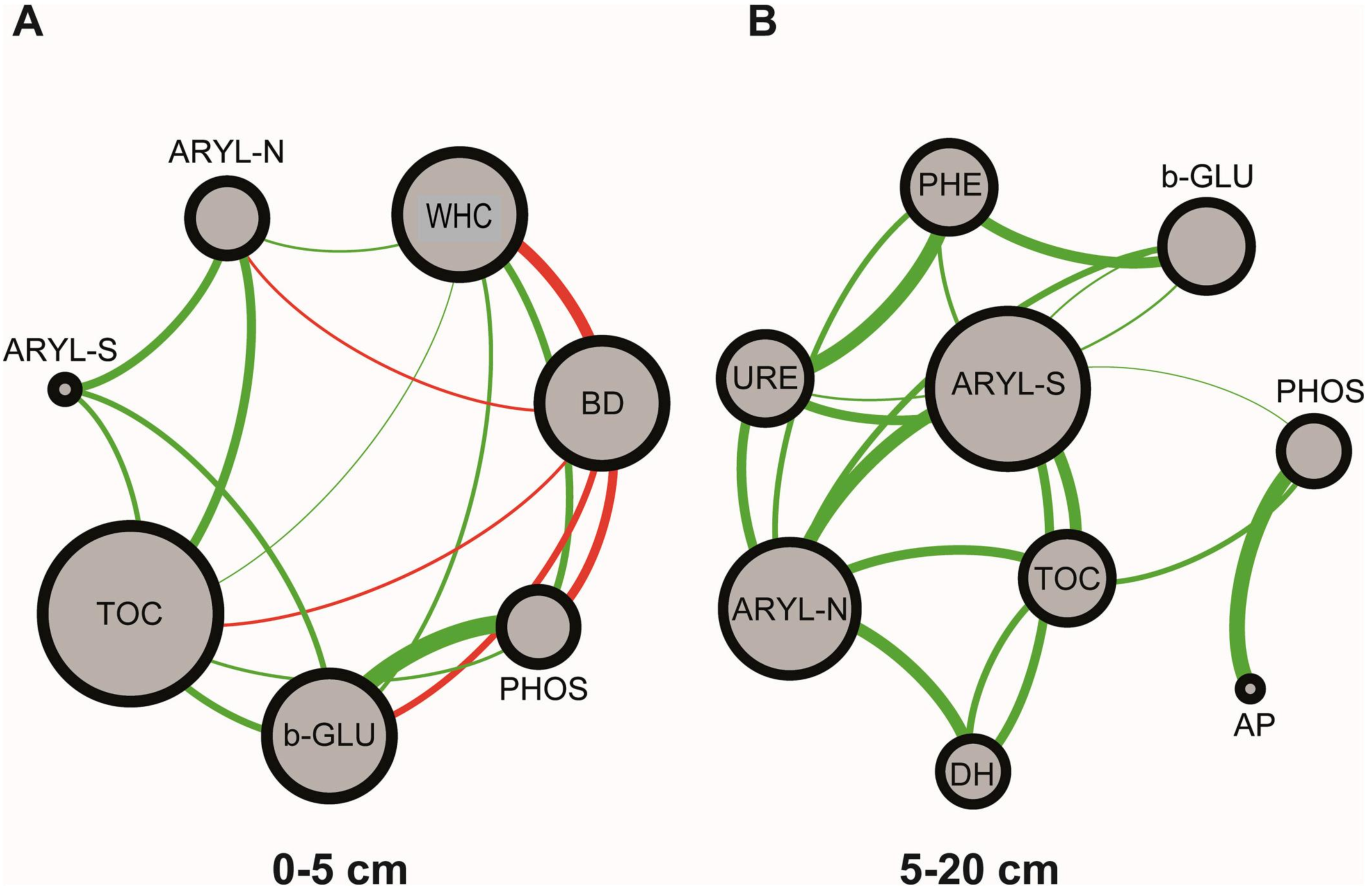

Fig. 2. Undirected graphs generated through Spearman's bivariate correlation (p-values <0.05) for soils at depths of 0–5 cm (A) and 5–20 cm (B). The circles (nodes) correspond to the soil variables and the lines (edges) correspond to the significant correlation coefficients between variables. Node size depends on its degree (number of significant correlations of a node). Edges are green for positive correlations and red for negative; edge widths correspond to its correlation coefficient. AP = Available Phosphorous, ARYL-N = arylamidase, ARYL-S = arylsulfatase, BD = Bulk Density, b-GLU = beta-glucosidase, DH = dehydrogenase, PHE = phenoloxidase, PHOS = phosphatase, TOC = Total Organic Carbon, URE = urease, WHC = Soil Water Holding Capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Soil properties network

Bivariate correlations showed that the number of edges (average degree) of both the surface (0–5 cm) and subsurface horizon (5–20 cm) was similar, but that the subsurface network had greater weights (weighted average degree) than the surface network (Table 1). In both horizons a single group of variables (module) was established, since the modularity of the networks was very close to zero. Other network metrics such as transitivity and diameter were very similar between both networks. In the surface horizon, the variables with the highest degree – and therefore with the greatest importance in the network – were the TOC content and the soil physical variables related to soil compaction, WHC and BD (Fig. 2A). TOC content and WHC had a positive role in the network, while BD had a negative role as it was negatively correlated with the rest of the variables. Enzyme activities had little importance in this soil surface horizon network. In contrast, the variables with the greatest degree, and hence the greatest importance, in the soil subsurface network were the activities of three key enzymes for the functioning of the biogeochemical cycles of the macronutrients that limit plant growth (S, N and P), arylsulfatase, arylamidase and phosphatase (Fig. 2B). In this network all the correlations were positive, and the influence of the physical soil variables disappeared.

3.2. Influence of plant community and soil depth on soil properties

Of the two factors tested (plant community and soil depth) for WHC, only plant community was observed to be significant, explaining 40 % of the total variance (two-way ANOVA, Table 2). However, no significant differences between communities were observed when soil depth was considered (Fig. 3A). Both factors were significant for BD, explaining approximately 79 % of total variance (two-way ANOVA, Table 2). In this case, the plant community had stronger relationships than the sampling depth. BD was higher in the subsurface horizon than in the surface horizon in all the plant communities, but was only significant in annual grasslands and perennial forbs (Fig. 3B). When comparing the communities, soils in the surface horizon had a significantly higher BD on

Table 2

Results of two-way ANOVA calculated for soil physical variables (Soil Water Holding Capacity = WHC; Bulk Density = BD), available nutrients (Total Organic Carbon = TOC; Available Phosphorous = AP; NH4-N = Available Ammonium) and enzyme activities (Dehydrogenase, β-Glucosidase, Phenoloxidase, Arylamidase, Urease, Arylsulfatase, Phosphatase) considering the plant community (Community) as a between-subjects variable, the soil depth (Depth) as a within-subjects variable and their interaction (Community * Depth).

	Variable	Factor	gl	F	p	Partial eta squared (η_p^2)
Physical variables	WHC	Model	7	1.782	0.165	0.454
		Community	3	3.393	0.046	0.404
		Depth	1	0.664	0.426	0.042
		Community * Depth	3	0.343	0.795	0.064
	BD	Model	7	7.896	<0.001	0.787
		Community	3	12.425	<0.001	0.713
		Depth	1	10.805	0.005	0.419
		Community * Depth	3	2.086	0.145	0.294
C cycle	TOC	Model	7	6.584	0.001	0.754
		Community	3	8.717	0.001	0.635
		Depth	1	19.865	<0.001	0.570
		Community * Depth	3	0.274	0.843	0.052
	Dehydrogenase	Model	7	5.576	0.003	0.722
		Community	3	3.330	0.048	0.400
		Depth	1	28.865	<0.001	0.658
		Community * Depth	3	0.313	0.816	0.059
	β-Glucosidase	Model	7	6.643	0.001	0.756
		Community	3	5.216	0.011	0.511
		Depth	1	28.379	<0.001	0.654
		Community * Depth	3	0.582	0.636	0.104
	Phenoloxidase	Model	7	3.046	0.033	0.587
		Community	3	6.158	0.006	0.552
		Depth	1	0.215	0.649	0.014
		Community * Depth	3	0.633	0.605	0.112
N cycle	NH4-N	Model	7	0.381	0.899	0.151
		Community	3	0.526	0.671	0.095
		Depth	1	0.001	0.973	0.000
		Community * Depth	3	0.380	0.769	0.071
	Arylamidase	Model	7	6.332	0.001	0.747
		Community	3	5.054	0.013	0.503
		Depth	1	29.914	<0.001	0.666
		Community * Depth	3	0.070	0.975	0.014
	Urease	Model	7	5.287	0.003	0.712
		Community	3	2.411	0.107	0.325
		Depth	1	28.614	<0.001	0.656
		Community * Depth	3	0.548	0.657	0.099
S cycle	Arylsulfatase	Model	7	3.728	0.015	0.635
		Community	3	3.089	0.059	0.382
		Depth	1	14.420	0.002	0.490
		Community * Depth	3	0.730	0.550	0.127
P cycle	AP	Model	7	4.935	0.005	0.697
		Community	3	8.593	0.001	0.632
		Depth	1	8.724	0.010	0.368
		Community * Depth	3	0.071	0.974	0.014
	Phosphatase	Model	7	5.517	0.003	0.720
		Community	3	5.148	0.012	0.507
		Depth	1	18.939	0.001	0.558
		Community * Depth	3	0.978	0.429	0.164

trampled soils than on roadsides and perennial forbs. In the subsurface horizon, this variable showed significant differences between trampled vegetation and annual grasslands with roadsides.

Plant community and soil depth were significant for TOC and explained 75 % of the variance between the two factors (two-way ANOVA, Table 2). TOC content was higher in the surface horizon in all cases, but significant differences between depths were only detected in annual grasslands and perennial forbs (Fig. 4A). At the surface horizon level, significant differences in plant communities were only found between vegetation on trampled soils and perennial forbs, whereas the other communities had intermediate values. DH activity, which reveals the activity of populations of living soil organisms, showed that the factor that determines this activity was soil depth (Table 2), where the surface horizon had a significantly higher activity in all the communities except roadside vegetation (Fig. 4B). b-GLU activity showed a very similar behaviour to TOC, and was significantly influenced by the two factors, explaining a variance of 76 % (Table 2). This enzyme activity was higher in the surface than in the subsurface horizon in all the plant communities, and significantly higher in all except trampled soils (Fig. 4C). The surface soil horizon under perennial forbs had a significantly higher b-GLU activity compared to trampled soils, with the other communities presenting intermediate values. PHE activity, an enzyme responsible for metabolising recalcitrant organic matter, was more influenced by the plant community than by the sampling depth (Table 2). However, no significant differences were observed between communities (Fig. 4D).

Aryl-N activity, a key enzyme in the N cycle, was significantly related to plant community and soil depth, explaining 75 % of the variance (Table 2). The activity of this enzyme was significantly higher in the surface horizon of all the vegetation types (Fig. 5A). Significant differences were also detected between trampled soils and perennial forbs in the soil surface horizon. In the case of URE activity, depth was the only significant factor, explaining 71 % of the variance (two-way ANOVA, Table 2), and the activity of this enzyme was significantly higher in the surface horizon for all the plant communities except for perennial forbs (Fig. 5B). Aryl-S activity, with a similar pattern to that of URE, was only

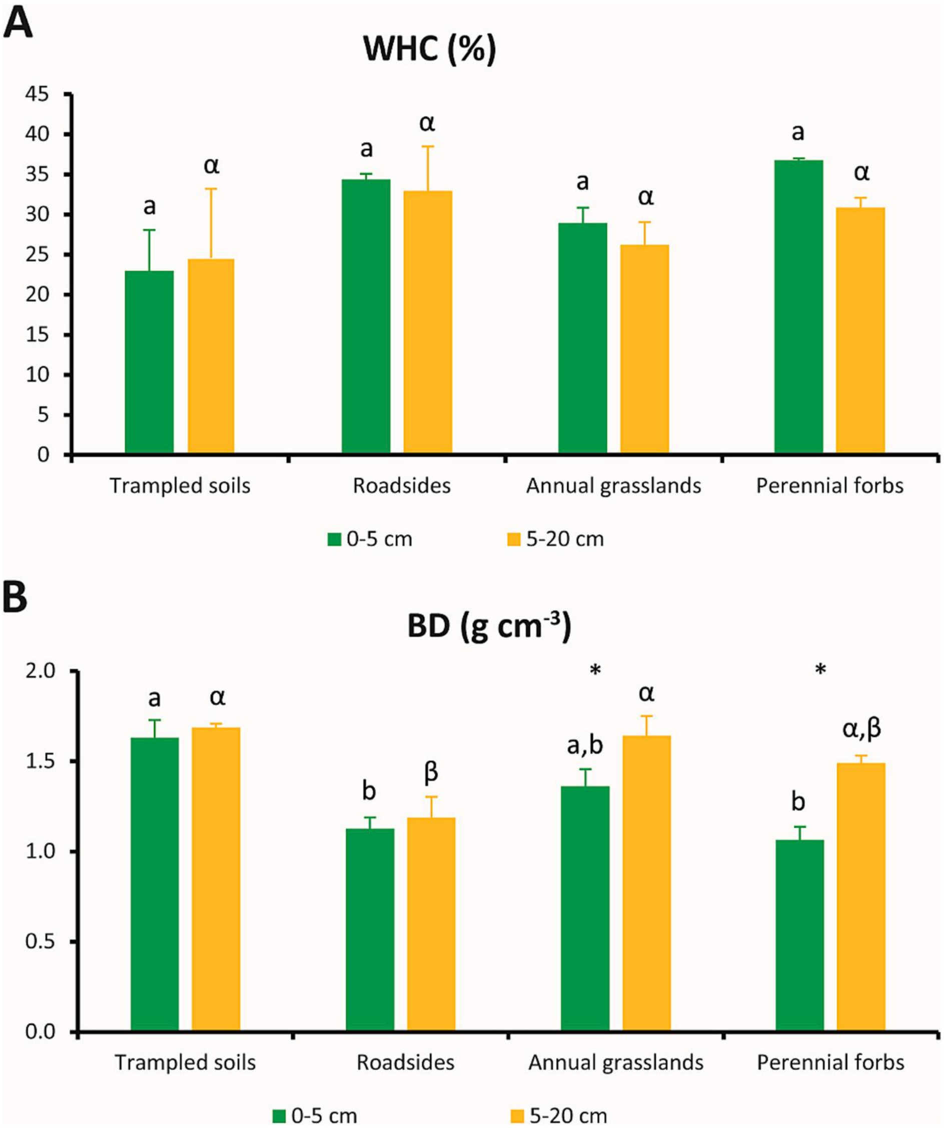

Fig. 3. Soil water holding capacity and bulk density in the surface (0–5 cm) and subsurface (5–20 cm) soil horizon in four habitats (trampled soils, roadsides, annual grasslands, perennial forbs). Latin and Greek letters indicate significant differences in horizon between habitats, and asterisks indicate significant differences between horizons within the same habitat (two-way ANOVA with Bonferroni test, $P < 0.05$). Error bars represent standard error ($n = 3$). WHC = soil water holding capacity, BD = bulk density.

influenced by soil depth (49 % of the variance explained by this factor). Aryl-S had a higher significant activity in the surface soil for roadsides and perennial forbs (Fig. 5C). AP was significantly related only to the plant community (Table 2), where significant differences were detected between annual grasslands and perennial forbs in the two soil horizons (Fig. 5D). The difference between roadsides and annual grasslands compared to perennial forbs was also significant in the subsurface horizon. Both factors (plant community and soil depth) exhibited a significant influence for PHOS activity, explaining 73 % of the variance their combined effects (two-way ANOVA, Table 2). The activity of this key enzyme in the P cycle was significantly higher in the upper horizon in all the sampled communities, except in trampled soils (Fig. 5E). At the surface horizon this activity was significantly higher in perennial forbs compared to trampled soils, with the other communities at intermediate values. This pattern was very similar to that found for TOC content and Aryl-N activity.

4. Discussion

Soils in natural environments have been found to have higher network density than anthropogenic habitats (Creamer et al., 2016). Our results clearly showed that in the surface horizon the physical-chemical variables related to soil compaction played a significant role in ecosystem functions. In contrast, in the subsurface horizon the variables presenting the greatest weight involved the key enzymes associated with the functioning of macronutrient cycles. This geo-biochemical dissociation between soil horizons in terms of factors influencing organic matter dynamics, where macronutrient cycles are more effectively assemblage in the subsurface horizon, can be explained not only by the direct activities that create soil disturbance but also by the deposition of air pollutants. Anthropic activities increase the deposition of nutrients in urban ecosystems, causing changes in the composition of plant and soil organisms and in turn impacting on soil processes such as organic matter mineralisation and nutrient cycling (Galloway et al., 2008; Erisman et al., 2013). The surface soil horizon is directly exposed to organic contaminants and atmospheric deposition, which can explain the

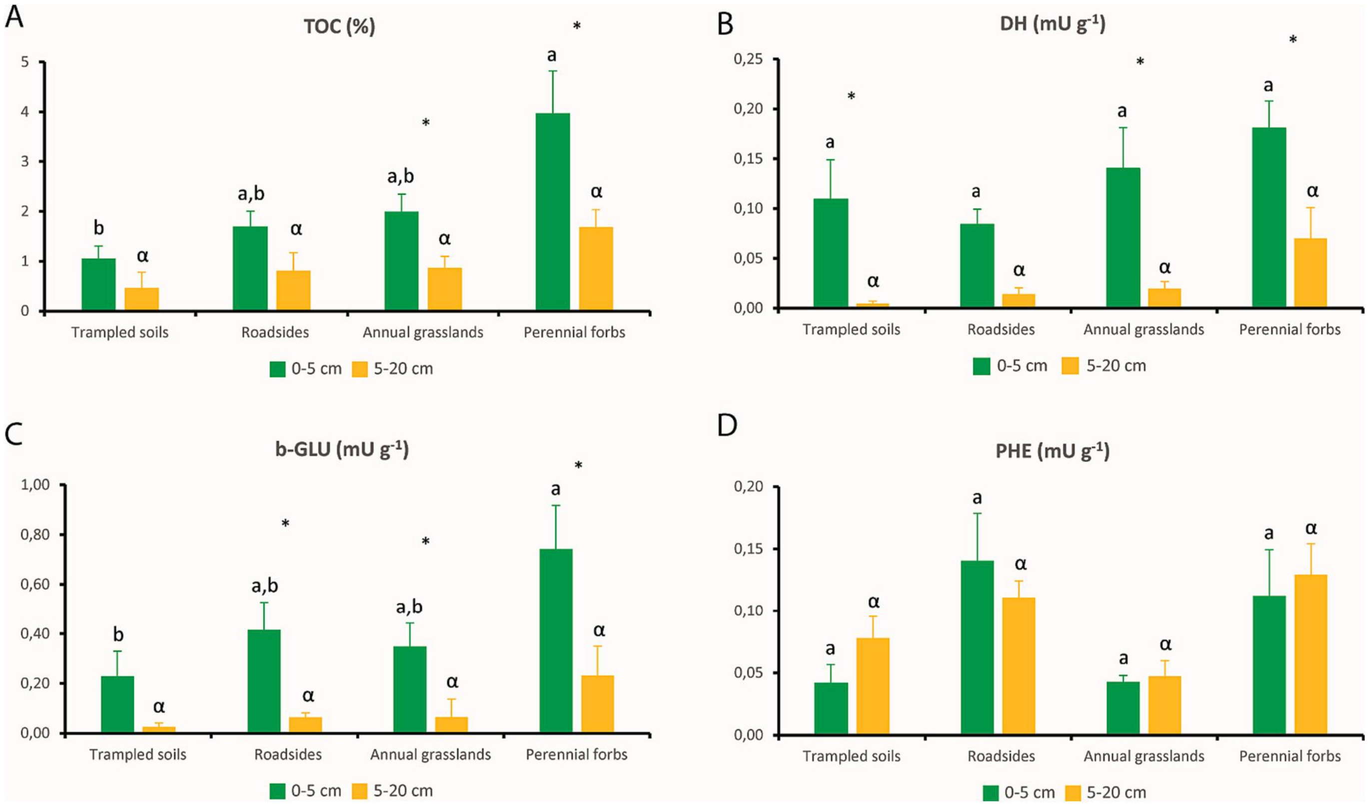

Fig. 4. Soil TOC content and enzyme activities related to the C cycle in the surface (0–5 cm) and subsurface (5–20 cm) soil horizon in four habitats (trampled soils, roadsides, annual grasslands, perennial forbs). Latin and Greek letters indicate significant differences in horizon between habitats, and asterisks indicate significant differences between horizons within the same habitat (two-way ANOVA with Bonferroni test, $P < 0.05$). Error bars represent standard error ($n = 3$). TOC = total organic carbon, DH = dehydrogenase, b-GLU = beta-glucosidase and PHE = phenoloxidase.

decreasing vertical trend in their content from topsoil to subsoil (Düring et al., 2002; Fabietti et al., 2010). N enrichment diminishes microbial biomass and abundance, reduces bacterial diversity and decreases the soil C mineralisation rate (Chen et al., 2019). Specifically, total N deposition in cities predominately comprises chemically reduced forms of N such as ammonia, which promotes eutrophication and soil acidification (Decina et al., 2020). The weak relationships we found between the key enzymes in the N and S cycles with the organic fraction in the upper soil horizon compared to the strong relationship of these enzymes and the dynamics of soil organic matter in the subsurface horizon could likely be due to this atmospheric deposition of nutrients that causes the disruption of these cycles. Soil horizons act as interacting yet distinct functional units in terms of organic matter dynamics and are likely to respond differently to external forcing (Matteodo et al., 2018). It is noteworthy that in our network study all habitats were analysed together. Subsequent studies should study them separately to verify whether this dissociation in the soil horizons is independent of the habitats.

According to our results, the soils under trampled soils and roadsides presented the lowest number of significant differences between horizons in the soil parameters studied. We also found an evident difference in BD between trampled soils (highest) and roadside vegetation (lowest) independently of the soil horizon analysed. Human recreation leads to soil compaction, causing a decline in total porosity and WHC and a reduction in vegetation cover and height (Sun and Liddle, 1993; Li et al., 2022; Liu et al., 2023). In addition to the change in vegetation structure, soil compaction determines floristic composition and hence the vegetation type (Molina et al., 2023). Intense compaction by trampling also affects the structure and function of the soil microbial community, and reduces the relative abundance of ectomycorrhizal fungi (Liu et al., 2023). Trampling in UGs leads to poorer ecological services in terms of biodiversity conservation, soil carbon storage, nutrient cycling and water regulation (Molina et al., 2023). However, a higher soil porosity does not necessarily result in an improvement in ecosystem functions, since according to our results, roadside vegetation was developed on soils with higher PHE and lower DH activities, which may suggest that they were subjected to stressed microbial activity.

Our results also highlighted that the soils under annual grasslands and perennial forbs presented the greatest number of significant differences between horizons in the soil parameters studied. Additionally, significant differences were found in AP between perennial forbs (highest) and annual grasslands (lowest) regardless of soil depth. Nutrient enrichment with limiting elements such as nitrogen (N) and phosphorous are considered to have a negative long-term effect on plant community composition, species richness, plant diversity and ecosystem productivity (Isbell et al., 2013; Seabloom et al., 2021). Given the above, we found that UV types have a potential to serve as proxies for soil compaction and nutrient status across cities. Our data can be considered a promising start to an important and much needed study area, but additional sampling in other cities is required at the very least to see the strength of these patterns.

The surface horizon (0–5 cm) showed the greatest number of significant soil differences between habitats. Specifically, perennial forbs (with higher values) were differentiated from trampled soils (with lower values) for TOC and enzymatic activities such as b-GLU, Aryl-N, PHOS. Although the amount of organic matter stored in urban soils is highly variable in space and time (Lorenz and Lal, 2009), the quantities are comparable to soils in natural and agricultural areas (Vasenev et al., 2013). When establishing the organic matter contribution of UGs and their habitats, it is therefore important to determine their role in their related ecosystem service such as carbon storage. It should be noted that, in comparison with natural ecosystems, urban ecosystems exhibit higher

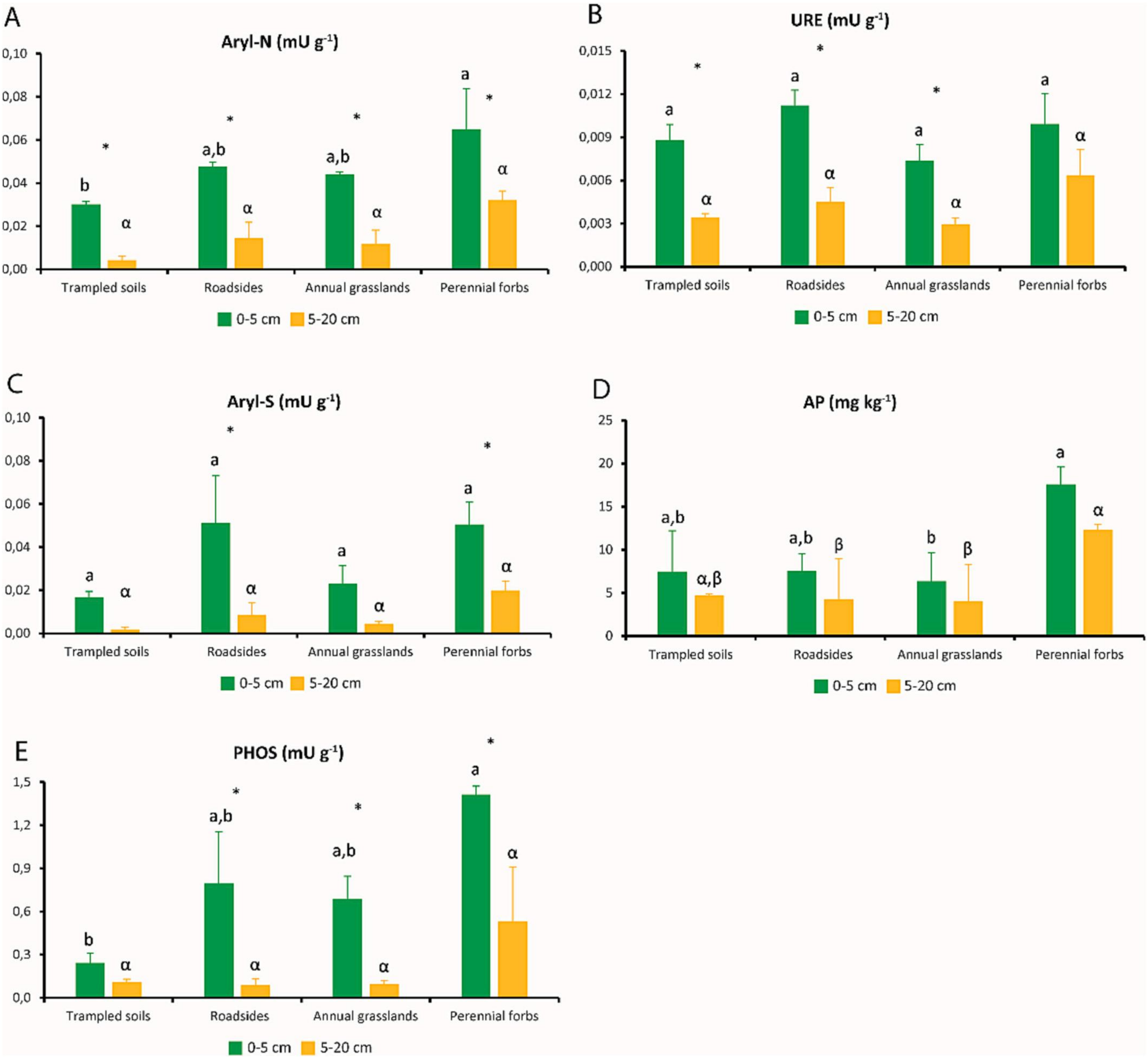

Fig. 5. Enzyme activities related to the N, S and P cycle and available phosphorous (AP) content in the surface (0–5 cm) and subsurface (5–20 cm) soil horizon in four habitats (trampled soils, roadsides, annual grasslands, perennial forbs). Latin and Greek letters indicate significant differences in horizon between habitats, and asterisks indicate significant differences between horizons within the same habitat (two-way ANOVA with Bonferroni test, $P < 0.05$). Error bars represent standard error ($n = 3$). ARYL-N = arylamidase, URE = urease, ARYL-S = arylsulfatase, PHOS = phosphatase.

proportions of soil microbial genes associated with faster nutrient cycling (Delgado-Baquerizo et al., 2021), and their distribution is likely heterogeneous throughout green spaces. Perennial forbs with Malva show high primary productivity (Molina et al., 2023). According to our results, perennial forbs had the highest carbon content in the soil – although only in the surface horizon – and the highest nutrient availability. They also developed in soils with high enzyme activity related to the degradation of both labile and recalcitrant organic substrates. All considered, this habitat appears to be subjected to faster nutrient cycling, and its ecosystem functions seem to be less efficient with regard to carbon storage.

5. Conclusions

All urban services have their origins in natural capital, which includes biotic and abiotic components and abiotic processes (Tan et al., 2020). The present study, which focused on soil disturbance gradients related to organic matter content and compaction in a Mediterranean urban greenspace, revealed a substantial dissociation between shallow horizons (0–5, 5–20 cm) in terms of soil properties. Physical-chemical parameters were the main drivers in the surface horizon (0–5 cm), whereas biological properties played the most significant role in the subsurface horizon (5–20 cm). Our results also showed that the soil disturbance gradients differentiated better between vegetation types in relation to the surface soil horizon. Urban soil functioning is therefore conditioned by anthropogenic disturbances, the effects of which vary according to soil depth. Furthermore, the surface horizon is the most closely correlated with the spatial response of the vegetation.

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CRediT authorship contribution statement

José Antonio Molina and José Ramón Quintana conceived the ideas, designed the analysis, collected and curated the data, performed the analysis, interpreted the results and led the writing of the manuscript. Juan Pedro Martín-Sanz performed the analysis of the networks and interpreted the results. All authors contributed data and critically reviewed the manuscript drafts.

Declaration of competing interest

All the co-authors have reviewed and agree with the contents of the manuscript, and there is no financial interest to report. We certify that the submission is an original work and has neither been published in any other journal nor is under consideration for publication by any other publisher. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available on request from the data custodians (jmabril@ucm.es; jrquinta@ucm.es), in VEGAS database (givid).

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