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Physical properties of the urban soils of Santiago de Compostela (Spain)

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Abstract

Purpose Poor physical conditions are a typical feature of urban soils that reduce their functionality regarding plant production or the water cycle. However, the increasing importance of urbanization makes it necessary to carry out additional research on physical properties of urban soils.

Methods In this work, we have studied 64 urban soils in Santiago de Compostela (Spain), over different parent materials and under several land uses. We assessed their physical properties in the field and laboratory, with measures of bulk density and porosity, water holding capacity, aggregate stability and water-dispersible clay, permeability and resistance to penetration. The erosion risk was assessed by estimation of the k factor in the RUSLE.

Results The results show that the soils present heterogeneous physical properties, as common in urban soils. As a result of high organic matter and Fe contents, the soils present low bulk densities and high aggregate stability. Compaction issues are widespread but dependent on land use: in general soils under urban agriculture use present higher permeability and lower compaction levels than urban grasslands and forests. High infiltration values observed despite compaction are likely due to the abundance of coarse fragments and preferential flow.

Conclusion Overall, urban soils have potentially low erosion risk as shown by the K factor values, but sound management is essential to keep actual erosion rates down, because relief, climatic factors as well as human behavior are susceptible of increasing erosion risk at some points.

Keywords Urbanization · Compaction · Permeability · Soil structure

1 Introduction

Intensification of urbanization in the last decades is bringing new environmental problems and challenges, as population growth concentrates population, activities and infrastructures in increasingly large urban areas. Urban expansion and the activities associated have significant impacts on land use and soil health: urban growth and infrastructures occupy and/or destroy fertile soils, which are also sealed and/or compacted, submitted to pollution processes from industry and traffic, as well as from waste disposal (Bechet et al. 2019).

Soil physical degradation is one of the most obvious negative impacts of urbanization because infrastructure works often need physical modification of soil, including removal of topsoil horizons, excavation, or filling of new soil layers. These practices alter the soil profile and its properties by stripping away topsoil to accommodate additional fill to grade to relief specifications (Johnston et al. 2016). Compaction is the main feature of physical degradation of urban soil. This is a widespread issue that can be either unintentional, as a result of repeated traffic from heavy machinery, or deliberate to strengthen soils for engineered loads, since many works require packing soils to high bulk densities for load bearing (Scharenbroch et al. 2005; Pearson et al. 2013). Compaction results in decreased porosity and pore connectivity, increased bulk density, and greater profile heterogeneity (Burghardt 1994; Jim 1998; Morel et al. 2015). Soil structure is negatively affected because of deformation of the pore lay-out, disaggregation, and formation of blocky or platy structures (Gorbov et al. 2016). Other soil properties also impacted by urbanization include texture and particle

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size, with are typically dominated by sand, high contents in coarse materials and artefacts, or low water holding capacity (Baumgartl 1998; Morel et al. 2015).

The same as in soils in non-urban areas, urban soils play an essential role in water cycle regulation and water supply to plants as well as erosion processes and phenomena. Thus, poor physical properties resulting from the degradation processes associated to urbanization activities may have negative impacts on soil and ecosystem functions and will expectedly result in loss of functionality of urban soils. The most common problems in this sense are related to widespread sealing and compaction issues, which reduce porosity inhibiting rainwater infiltration and increasing surface runoff and peak discharge rates, create excess stormwater runoff that may contribute to the malfunction of wastewater infrastructure, increase in flood and degradation of surface water quality (Gregory et al. 2006; Shuster et al. 2015; Johnston et al. 2016). Lower drainage of urban soils also affects the diffusion of oxygen and other gases (Huong and Pathirana 2013; Yang and Zhang 2011), potentially causing physiological stress to urban vegetation. Finally, erosion in urban areas is exacerbated by the increased volume and velocity of runoff from impervious surfaces, also increasing sediment load in urban streams (Prokof'eva et al. 2020; Rate 2022). All in all, this results in a drastic disturbance of the water cycle and has negative impacts on soil conditions for plant growth, representing an important problem for the sustainability of urban areas.

Thus, urban soils bring a new set of conditions, in many cases different from non-urban soils, which must be understood and addressed to mitigate any reduction in the ecological services provided by the landscapes. Although the number of studies in this topic is increasing in recent years, along with the intensification of urbanization and interest in greener cities as part of the Sustainable Development Goals for 2030, further research is still necessary. Our knowledge is limited by the substantial short-scale heterogeneity in urban soil physical properties, which can be found in the vertical as well as in the horizontal dimension, with strong differences between horizons due to high contents in coarse materials and presence of layers of contrasting properties and composition (Baumgartl 1998; Horn et al. 2017; Rate 2022). Besides, existing studies so far have focused preferentially on some physical properties, in particular compaction, whereas, for example, reports on aggregate stability or water holding capacity are less common (Yang and Zhang 2011; Pearson et al. 2013; Wei et al. 2014; Whitehead et al. 2021).

With the objective of increasing our knowledge on urban soil physical properties and provide information for sustainable land management in urban areas, we have performed a comprehensive study of soil physical properties, including permeability, compaction, water holding capacity and erosion risk, in the city of Santiago de Compostela (Spain). The city presents a high relative surface of green areas, a remarkable diversity of parent materials, and a variety of land uses and vegetation that offer great opportunities for the study of factors that determine the properties and functions of urban soils. This work is part of an exhaustive study which also includes morphology, classification, fertility, biology and pollution, a comprehensive approach to the evaluation of urban soils that has not been undertaken to date in any other city in Spain.

2 Materials and methods

2.1 Study area

The municipality of Santiago de Compostela, located in the northwest of the Iberian Peninsula, has an area of 222 km^2 and counts 97,000 inhabitants. The climate is warm and wet and, according to the Köppen-Geiger Climate Classification, the city is located in the temperate oceanic climate (Cfb) zone (Kottek et al. 2006). The mean annual air temperature is 13.0 ºC; August is the warmest month (mean air temperature 19 °C) and January is the coldest one (mean air temperature: 8 °C). The average annual precipitation is 1,787 mm. The relatively low values for potential evapotranspiration (< 300 mm in summer and 50–100 mm in winter) result in a positive water balance (600–800 mm) (Martínez Cortizas and Pérez Alberti 1999). The city presents an important geological diversity that includes granites and metamorphic rocks of the metamorphic massif known as the Ordes Complex, with schists, gneiss and amphibolites (Díaz-García 1990). The soils found in the city would be classified as Umbric Leptosols, Leptic, Haplic and Cambic Umbrisols, Skeletic Transportic Regosols, and Urbic and Ekranic Technosols (Paradelo et al. 2022).

2.2 Soils

We studied non-sealed urban soils at 64 points, over several geological materials and under different vegetations and land uses (Fig. 1, Table S1). Since grasslands are the most common surfaces in the green areas in Santiago, most soils (n = 35) correspond to this type of land use, followed by urban forest areas (n = 14), and urban and periurban agriculture soils (n = 14), plus a green roof. Regarding lithology of the parent material, 44% of the soils are developed on schist, 23% on granite or granite mixed with schist, 23% on gneiss and 8% on amphibolites. Selected physicochemical properties of the soils are presented in Supplementary material (Table S2) and further information can be found in previous publications (Herbón et al. 2021; Paradelo et al. 2021, 2023; Gómez-Brandón et al. 2022; Probst et al. 2023).

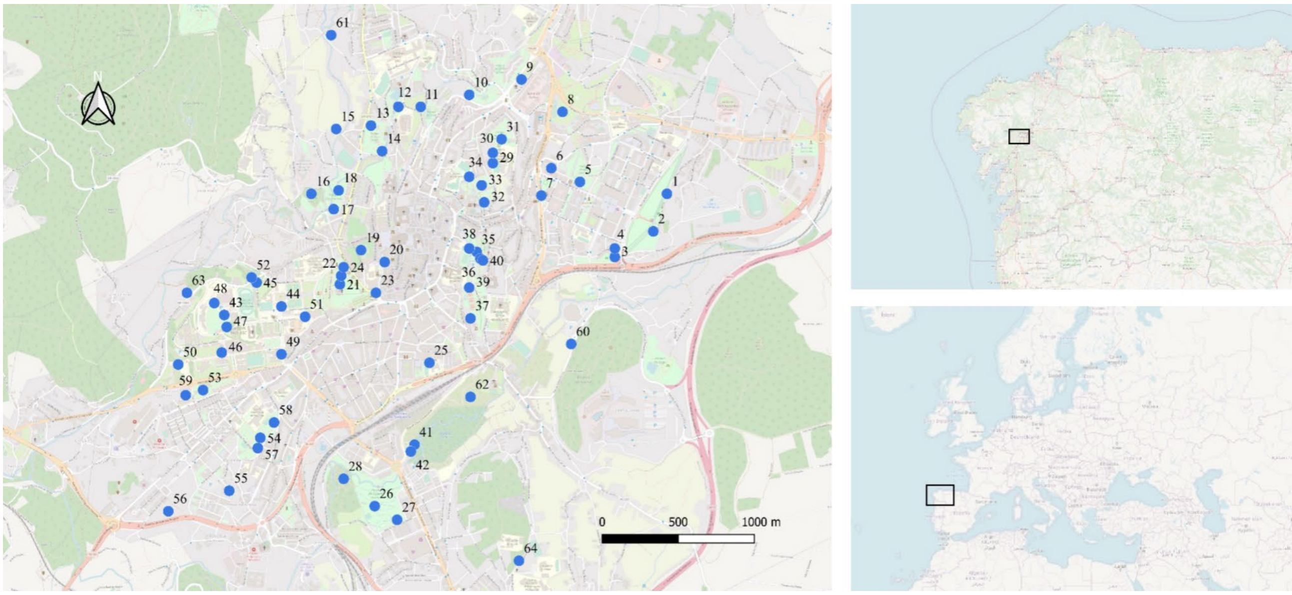

Fig. 1 Location of the points studied

2.3 Sampling and laboratory measurements

Three undisturbed samples (0–5 cm) were taken at each point using 100 cm^3 steel cylinders for bulk density determination, and composite samples (soil depth 0–20 cm) were taken with an Edelmann auger by mixing 4–5 subsamples at each point. Soils were air-dried at the laboratory and passed through a 2-mm sieve before analysis. All analyses were performed by triplicate.

Particle density was determined in ground (< 50 µm) dry soil by the pycnometer method, using toluene as the filling liquid. Total porosity was calculated using particle density and bulk density values.

Water holding capacity was measured using a Richards plate extractor following the method described by Guitián and Carballas (1976). The available water capacity was determined as the difference between water retention at field capacity (FC), obtained at a pressure of 0.1 bar, and at the permanent wilting point (WP), obtained at 15.5 bar (1 bar = 0.1 MPa).

Aggregate stability was measured in 1–2 mm aggregates separated from non-sieved soil, following the method by Kemper and Rosenau (1986), after agitating 10 g of 1–2 mm aggregates in water for 2 min. Water-stable aggregates (WSA) were expressed as weight percentage with respect to the total weight of aggregates.

Water-dispersible clay was extracted as explained in Paradelo et al. (2013). For the determination, 10 g of air-dry soil were shaken with 50 mL of deionized water for one hour in 100-mL plastic flasks. Suspensions were allowed to settle for 8 h at 20 ºC. A 20-mL aliquot was taken at a depth of 10 cm with a Robinson pipette, transferred to weighed aluminium capsules, dried for 48 h at 105 °C and weighed to determine the amount of water dispersible clay, which was expressed as g clay 100 g^{-1} of oven-dried soil (105 °C).

2.4 Field measurements

Permeability was determined where possible (slope limitations existed in some points) by measuring infiltration using a single disc infiltrometer, and infiltration classes were established according to those given by U.S.D.A. (1999). Compaction was assessed by measuring penetration resistance using an Eijkelkamp hand penetrometer. Penetration resistance was recorded at depth increments of 5 cm, with maximum values for the top 5 cm and selected depth profiles presented here.

2.5 Erosion risk assessment

When possible (i.e., when all required measures have been performed, in particular permeability), soil erosion risk was estimated by calculating the *k* factor in the revised USLE equation, following the recommendations by Auerswald et al. (2014).

2.6 Statistics

ANOVA mixed model analysis was used to determine the influence of parent material and land use on the properties of the soils. The normality of data was checked using the Shapir-Wilk test. Data that did not pass the normality test were log-transformed for ANOVA. The homogeneity of variance was tested using the Levene test. When a significant effect of land use or lithology at a level of significance of $P < 0.05$ was found, the Tukey's multiple range test was used to separate groups. Pearson's correlation analyses between all the properties analyzed were also conducted, adjusted for multiple comparison. All statistical analyses were performed using the R statistical package for MacOSX version R 4.2.0 (R Core Team 2022) and the package R Commander version 2.6-1 (Fox and Bouchet-Valat 2019).

3 Results and discussion

A summary of the physical properties of the soils are shown in Table 1 along with ANOVA results for the influence of land use and lithology (the full dataset is included in Supplementary material, Table S3). Box and whisker plots are shown in Fig. 2, only for those cases where significant differences due to land uses or lithology have been found, whereas correlations of physical properties and other soil properties are shown in Table 2.

Soils presented in general good structure as shown by aggregate stability and water-dispersible clay. Very high aggregate stability values were obtained, with an average value of 86%, whereas the values for water-dispersible clay, also a measure of structural stability, were in general very low (under 1 g kg^{-1} or 8% of total clay). Aggregate stability was not influenced by lithology or land use, whereas water-dispersible clay was higher in soils over amphibolite due to their higher total clay contents. Both measures of structural stability were significantly correlated between them; in addition, water-stable aggregates presented significant correlations with bulk density (negative) and porosity (positive), whereas water-dispersible clay was positively correlated with soil components such as total clay and free Fe. The high structural stability of these soils is a common feature in natural soils in the region and can be attributed to their high contents in organic matter and Fe oxides (Paradelo et al. 2021), which are determinant for soil structure in acid soils. Comparison with data from non-urban soils (Arias et al. 2016; Domínguez et al. 2019) shows that these urban soils present higher aggregate stability than comparable agricultural soils in the region, what might be due to the absence of tillage and other operations known to negatively impact this property in cultivated soils. This observation is contrary to reports in the literature stating that urbanization activities affect negatively

Table 1 Summary of physical properties plus ANOVA results

Soil	FC (g 100 g^{-1})	WP (g 100 g^{-1})	AWC (g 100 g^{-1})	WSA (%)	WDC (g kg^{-1})	WDC (g 100 g $clay^{-1}$)	Bd (Mg m^{-3})	Porosity (%)	PR 0–5 cm (kN cm^{-2})	Infiltration (cm h^{-1})	k factor
Minimum	*27*	*7*	*17*	*49*	*0.05*	*0.3*	*0.34*	*38*	*0.01*	*2*	*0.03*
Maximum	*69*	*33*	*45*	*94*	*1.00*	*7.7*	*1.41*	*85*	*0.34*	*187*	*0.15*
Mean	*40*	*14*	*25*	*86*	*0.27*	*1.8*	*0.95*	*61*	*0.14*	*56*	*0.07*
Median	*39*	*13*	*24*	*88*	*0.17*	*1.3*	*0.94*	*62*	*0.14*	*45*	*0.06*
Standard deviation	*8*	*5*	*6*	*8*	*0.23*	*1.5*	*0.21*	*9*	*0.08*	*39*	*0.03*
ANOVA											
Land use - F	*2.05*	*1.21*	*1.46*	*1.83*	*1.77*	*3.22*	*0.34*	*0.35*	*15.3*	*6.51*	*0.68*
p	*0.14*	*0.31*	*0.24*	*0.17*	*0.18*	*0.05*	*0.71*	*0.70*	*<0.001******	*0.004****	*0.51*
Lithology - F	*2.13*	*4.54*	*1.19*	*0.30*	*13.2*	*4.89*	*0.75*	*0.48*	*0.56*	*4.73*	*0.34*
p	*0.09*	*0.003****	*0.33*	*0.88*	*<0.001******	*0.002****	*0.56*	*0.75*	*0.69*	*0.003****	*0.85*
Land use x Lithology - F	*0.19*	*0.17*	*0.22*	*0.16*	*0.65*	*0.49*	*0.67*	*0.68*	*0.48*	*0.62*	*0.18*
p	*0.99*	*0.99*	*0.98*	*0.99*	*0.71*	*0.84*	*0.69*	*0.69*	*0.84*	*0.71*	*0.98*

Significance is indicated as follows: *Significant at a P-value of 0.05; **Significant at a P-value of 0.01; ***Significant at a P-value of 0.001

FC field capacity, *WP* wilting point, *AWC* available water capacity, *WSA* water-stable aggregates, *WDC* water-dispersible clay, *Bd* bulk density, *PR* penetration resistance

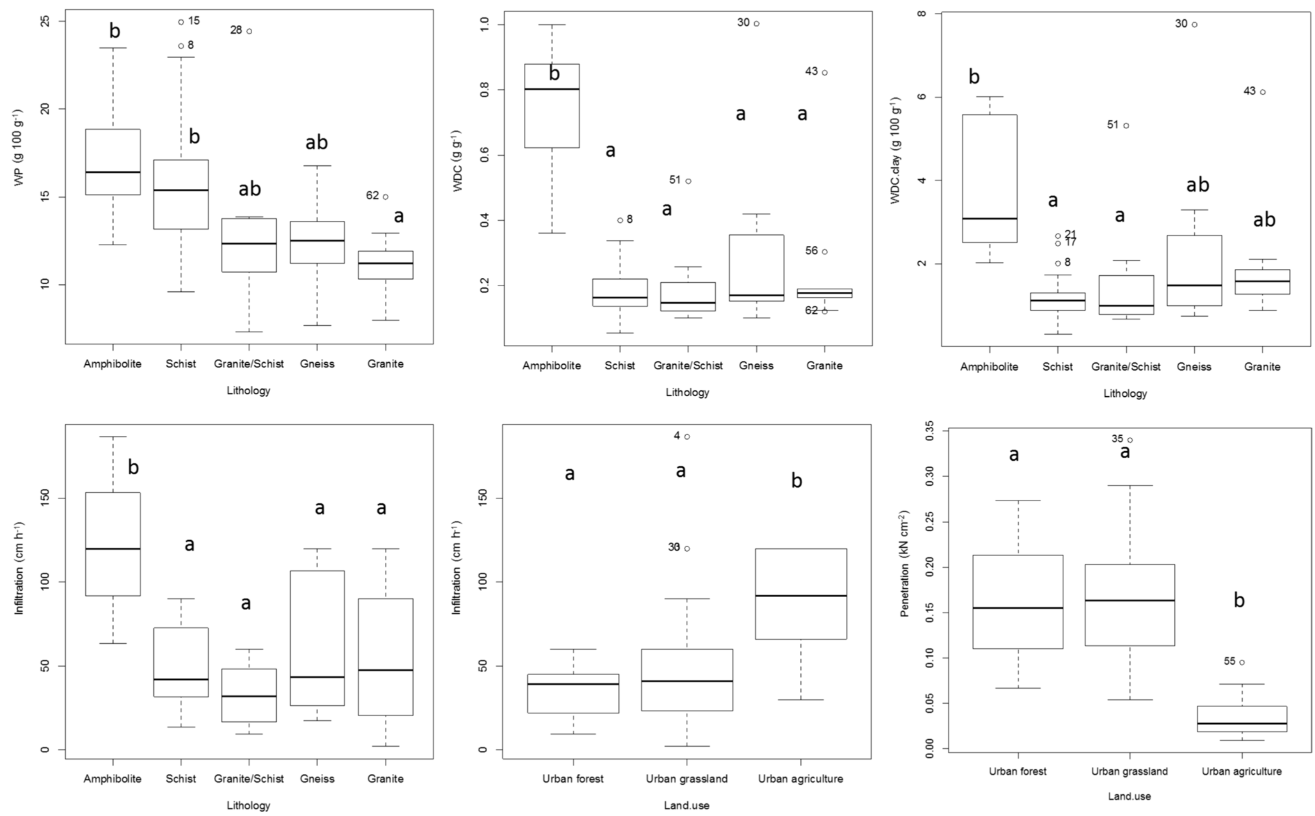

Fig. 2 Wilting point (WP) and water-dispersible clay (WDC) split by lithology; infiltration and penetration resistance split by land use and (only significant ANOVA results are plotted). Different letters indicate statistically significant differences between land uses in the Tukey test at $p < 0.05$

soil structure, mostly in a mechanical sense and especially in their early stages of development (Jim 1998; Gorbov et al. 2016; Rate 2022), and could be due to a low impact of urbanization in soils of this city (Paradelo et al. 2021). However, the number of works reporting aggregate stability in urban soils is still insufficient to provide insightful comparisons, highlighting the need for additional research in this subject.

Regarding the water holding capacity of the soils, field capacity ranged from to 27 to 69 g 100 g^{-1}, with a mean

Table 2 Correlation of physical properties with edaphic properties

	Clay	OC	CEC	Fe_{DCB}	Bd	Porosity	FC	WP	AWC	WSA	WDC	WDC/Clay	Infiltration	PR
Bd	-0.14	-0.52***	-0.41***	-0.03	1									
Porosity	0.14	0.44***	0.33**	0.06	-0.97***	1								
FC	0.49***	0.77***	0.69***	0.31*	-0.45***	0.41***	1							
WP	0.69***	0.76***	0.70***	0.48***	-0.38**	0.33**	0.72***	1						
AWC	0.18	0.52***	0.46***	0.09	-0.36**	0.33**	0.87***	0.28*	1					
WSA	0.25	0.10	0.24	0.17	-0.31*	0.38**	0.12	0.22	0.01	1				
WDC	0.34**	-0.26*	-0.19	0.53***	0.23	-0.21	-0.10	0.03	-0.16	-0.27*	1			
WDC/Clay	-0.03	-0.39**	-0.34**	0.22	0.30*	-0.27*	-0.27*	-0.24	-0.2	-0.42***	0.91***	1		
Infiltration	0.31*	-0.03	0.12	0.47***	0.22	-0.23	0.06	0.08	0.03	-0.03	0.39**	0.25	1	
PR	0.09	-0.09	-0.16	0.05	0.03	-0.04	0.01	0.12	-0.07	-0.10	0.14	0.18	-0.41**	1
k factor	0.23	-0.05	0.03	0.26	-0.05	0.08	0.33*	0.15	0.36*	-0.10	0.28	0.25	0.04	0.15

Significance of correlation is indicated as follows: *Significant at a P-value of 0.05; **Significant at a P-value of 0.01; ***Significant at a P-value of 0.001

OC organic carbon, *CEC* cation exchange capacity, Fe_{DCB} free iron compounds, *Bd* bulk density, *FC* field capacity, *WP* wilting point, *AWC* available water capacity, *WSA* water-stable aggregates, *WDC* water-dispersible clay, *PR* penetration resistance of 40 g 100 g^{-1}, whereas the wilting point ranged from 7 to 33 with a mean of 14 g 100 g^{-1}. As a result, available water capacity was medium (mean 25 g 100 g^{-1}), as corresponds to the dominant sandy-loam textures. There is a clear relationship of these values with bulk density and total porosity, with very significant negative and positive correlations, respectively, as well as with organic carbon, cation exchange capacity and clay content (Table 2). No correlations were found with other physical properties, and no influence of land use was observed either. Influence of lithology was found only for the wilting point, which was higher in amphibolite soils with respect to granite soils. Since the values of the wilting point are in general directly controlled by clay content (Marshall et al. 1996), this is a consequence of the heavier textures of the soils developed on amphibolites.

In general, the topsoils presented low bulk densities, ranging from 0.34 to 1.41 Mg m^{-3}, with a mean of 0.95 Mg m^{-3}, and high total porosity, from 38 to 85% with a mean of 61%. These bulk density values do not reach values that could represent restrictions to root development and plant growth. This is likely due to the high soil organic matter contents, as shown by the strong negative correlations of both properties with OC. Significant negative correlations were also found with aggregate stability, whereas differences due to land use or lithology were not observed in this case. Studies in other urban soils have generally reported high bulk density due to deliberate compaction and other processes already discussed, although in general with a wide range of values, in line with the typical high spatial heterogeneity of urban soil properties. For example, some researchers have found bulk density values in the same range as ours (Johnston et al. 2016; Horn et al. 2017) or even lower (Strain and Evans 1994). However, this is not the rule, and most studies in the literature report higher bulk density values for urban soils, often exceeding 1.6–1.7 Mg m^{-3} (Short et al. 1986; Jim 1998; Hamilton and Waddington 1999; Scharenbroch et al. 2005; Gregory et al. 2006; Pouyat et al. 2007; Langner et al. 2013). Although high bulk density is clearly a typical feature of urban soils, the extreme values reported can be due, at least in part, to the focus of many of these studies on compacted soils.

The study of soil compaction revealed a very high variation of penetration resistance in the top five centimeters, ranging from 0.01 to 0.34 kN cm^{-2} (Table 1). A clear influence of land use on compaction was detected, with significantly lower penetration resistance values in urban gardens with respect to urban grasslands and forests (Fig. 2). The range of values obtained here are in general agreement with the literature on urban soils (Gregory et al. 2006), although higher maximum values have also been reported (for example Johnston et al. 2016). In addition to occasional surface compaction problems, generalized subsurface compaction was observed here: many soils presented impenetrable layers at shallow depths, in general because of compacted layers of coarse materials with diverse grain sizes, but also in some cases by dense roots, and in two cases by continuous concrete layers (technic hard material). In general, penetration resistance increased with depth until reaching a maximum in most cases around 15 cm. Figure 3 presents selected profiles of penetration resistance, which show how subsoil compaction is clearly different between land uses, with lower absolute values in urban agriculture soils. Studies in the literature have also shown that subsurface compaction can appear more frequently that surface compaction, with maximum values at a depth of at 15–30 cm (Gregory et al. 2006). This fact is due to common landscaping practices, involving compaction of fill layers by machinery, which are later capped with a layer of imported topsoil for lawn development.

As shown in Table 1, infiltration ranged from low values (2 cm h^{-1}) to very high (187 cm h^{-1}). According to the USDA system, infiltration classes are mostly 1 (very rapid) or 2 (rapid), with very few cases of moderate or moderately rapid rates. The range of values found here agree in general with the literature, which shows wide variation in urban soils, in general around two-orders of magnitude, and moderate to rapid infiltration classes are dominant. Values for infiltration in the same order of magnitude of our results have been reported in several cities by Pitt et al. (2008), Pearson et al. (2013), Horn et al. (2017), Johnston et al. (2016), or Yang et al. (2008), whereas other authors have observed lower values, as expected in more compacted soils (Gregory et al. 2006; Woltemade 2010; Wang et al. 2018).

A significant negative correlation was found between compaction and infiltration, but not with any other soil property (Table 2), whereas land use influenced permeability in the same sense as happens with compaction, with significantly higher infiltration values in urban agriculture soils with respect to other uses (Fig. 2). Thus it is obvious that compaction due to management is the main factor determining infiltration in the urban soils studied here. In agreement with this, most authors have reported that compaction control infiltration in urban soils (Pitt et al. 2008; Gregory et al. 2006; Yang and Zhang 2011; Wang et al. 2018), although other researchers have observed that infiltration can also be controlled by edaphic properties such as texture (Pearson et al. 2013).

Even in the context of the high variability of this property in urban soils, the infiltration values in Santiago de Compostela, dominated by fast and very fast rates, are in general higher than expected considering penetration resistance measures. The most plausible explanation for this behavior is the existence of preferential flow through channels due to high contents in coarse elements in most soils (Paradelo et al. 2021). Other researchers have reported that preferential flow or multidirectional simultaneous flow are dominant in

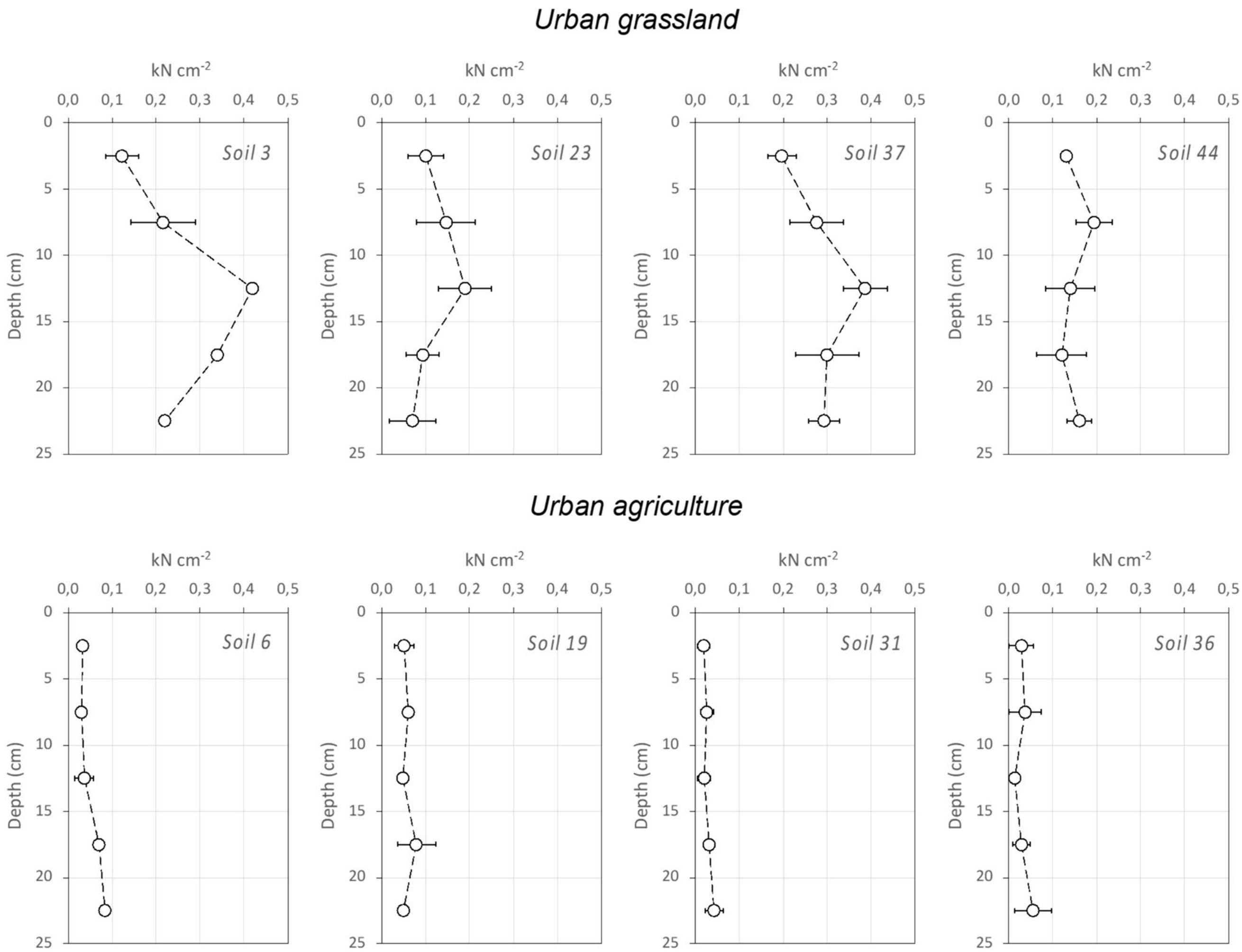

Fig. 3 Selected representative profiles of penetration resistance. Urban grassland on top, urban gardens on bottom. Urban forest soils were too shallow to obtain good penetration resistance profiles

urban soils due to mix with gravel, coal cinders, construction waste and other coarse materials, which easily form preferential flow controlled by gravitational pores (Yang et al. 2008; Horn et al. 2017; Wang et al. 2018).

Regarding the risk of erosion, calculations produced very low values for the k factor, always under 0.15 (Table 1), due to high aggregate stability, organic matter contents, and high permeability of the soils. No influence of land use or lithology was observed, and significant correlation was obtained only with water holding capacity, among all soil properties considered (Table 2). Despite the low potential erosion risk of the soils, the actual erosion rates will depend much on other factors such as green areas management, in particular in a city with a high rainfall, complicated relief and high pressure from walkers in a touristic center. Indeed, these conditions have led to the local apparition of areas with high runoff and erosion associated to compacted desire lines (paths for preferential transit) (Fig. S1). Although the soils in these desire lines have not been studied here, this point must be assessed and monitored in the future.

Based on these results, several management recommendations can be made in order to reduce soil erosion and compaction, as well as to improve water cycle functions in urban soils, with the general aim of increasing urban soil functionality and conservation. First, practices oriented at conserving and/or increasing soil organic matter levels must be favored, given the positive effect in soil structure and general physical properties and the fact that low organic matter contents negatively impact physical properties in many urban soils (Craul 1992; Bezuglova et al. 2018). Ways to achieve this goal include adopting a more natural management of green spaces, for example changing the mowing regime in lawns (Foti et al. 2021) or not removing fallen leaves in forest areas (Wang et al. 2018), as well as the use of organic amendments and manures to increase organic matter contents in urban gardens or degraded urban soils, or for soil construction in urban landscaping projects (Sax et al. 2017; Vidal-Beaudet et al. 2018; Ulm et al. 2019).

Besides, management practices oriented to reduce soil sealing and erosion are necessary, thus improving the functions related to the water cycle. The impermeabilized area should be limited by avoiding sealing of new surfaces, or even reduced by desealing activities. Regarding non-sealed areas, excessive compaction by machinery during landscaping and other works should be limited, and compaction by walkers should be controlled to avoid the development of desire lines, for example by considering the main directions of walkers when designing green areas. The measures to conserve organic matter mentioned above are also helpful in this sense, as organic matter reduces soil susceptibility to compaction and increases porosity and infiltration. Finally, restoration of areas degraded by soil compaction or erosion is another necessary action to protect urban soils. Overall, these measures will result in urban soils with better physical properties and will have positive effects on the water cycle and plant productivity of green areas.

4 Conclusions

The soils in the city of Santiago de Compostela show highly heterogeneous physical properties, as commonly found in urban soils. As a result of their high organic matter and Fe contents, the soils present good structural conditions, with low bulk densities and high aggregate stability and porosity. Compaction issues are widespread, in particular in the subsoil, but dependent on land use: in general soils under urban agriculture use present higher permeability and lower compaction levels than urban grasslands and forests. Soils presented high permeability despite local problems of compaction that do not reduce infiltration rates, likely due to the abundance of coarse fragments that create channels for preferential flow. In any case, further compaction must be avoided by judicious soil management of green areas. Overall, soils have potentially low erosion risk, but sound management is essential to keep actual erosion rates down. In this sense, measures to conserve/increase soil organic matter contents, to reduce soil sealing and erosion, and to protect and restore compacted soils must be adopted, in order to guarantee the correct functioning of the water cycle and plant productivity in urban green areas.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11368-024-03833-7.

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Data availability Data and materials supporting the results presented in this paper will be made available by the authors on reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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