

1 *Running title:* The Soils of Santiago de Compostela

2

3 **Core ideas**

4 The city of Santiago de Compostela has acid, organic matter-rich, sandy-loam soils.

5 Soils do not present the most typical features of very anthropized urban soils.

6 They are more similar to nearby natural/agricultural soils than to other urban soils.

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9 **Composition and Chemical Properties of the Soils of the City of**

10 **Santiago de Compostela (NW Spain)**

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17 **Abbreviations:** CEC, cation exchange capacity; EC, electric conductivity; OC, organic  
18 carbon; OM, organic matter.

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## ABSTRACT

21 Urban soils are still insufficiently known in many cities, despite the relevance of their  
22 functions in the urban environment. The city of Santiago de Compostela (NW Spain) offers  
23 interesting opportunities for the study of urban soils, because of its geological diversity and  
24 the variety of land use and vegetation. With the objective of increasing information about  
25 urban soils in Spain, in this work we have studied samples from 56 urban soils (0-20 cm)  
26 in this city, developed over different parent materials (granites, gneiss, schists and  
27 amphibolites) and under several land uses (lawn areas, forested areas, urban allotment  
28 gardens, periurban agricultural soils, and a green roof). The main physico-chemical  
29 properties of the soils were analyzed, including bulk density, texture, pH, organic matter,  
30 cation exchange capacity, available P and compounds of Fe and Al. The soils are coarse-  
31 textured (dominant texture is sandy loam), acid (pH in water from 4.7 to 6.9), with moderate  
32 to high in organic matter contents (13-137 g OC kg<sup>-1</sup>). Cation exchange capacity ranges  
33 from 9 to 36 cmol<sub>c</sub> kg<sup>-1</sup>, with Ca as the most abundant exchangeable cation in most soils  
34 and Al in the rest. Overall, the soils do not show several of the common features of other  
35 urban soils, such as alkalinity, high bulk density or large amounts of artifacts, and their  
36 composition is very similar to their natural counterparts in the region. The conservation of  
37 these soils with low degree of artificialization is essential because they are able to provide  
38 a wide range of ecosystem services.

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## INTRODUCTION

41 Urban soils are primary components of cities and main supports and suppliers of a large  
42 range of ecosystem services. Taking into account the major environmental issues that we  
43 confront due to the intensification of urbanization (United Nations, Department of

44 Economic and Social Affairs, Population Division, 2019), having soils in the cities capable  
45 of fulfilling a large variety of functions and providing the services expected by citizens is  
46 one of the main challenges for the future (Morel, 2015). Urban soils prevent flooding by  
47 allowing infiltration of water thus reducing surface-water run-off; improve air quality and  
48 are important for regulating the micro-climate and the heat island effect through vegetation  
49 and evaporation; store a considerable amount of soil organic carbon; can be a source of  
50 food through urban agriculture; and serve as fertile islands for plants and animals in  
51 increasingly densified cities (Morel et al., 2015; Tresch et al., 2018). Despite the  
52 fundamental role of soil in the urban ecosystem, it is considered as a secondary  
53 compartment beyond vegetation, ignored with regard to consideration of its functions and  
54 roles for the management of urban ecosystems (Morel et al., 2015). As a result, urban soils  
55 are an insufficiently recognized resource for the conception and construction of sustainable  
56 cities (Morel et al., 2015; Blanchart et al., 2018).

57 This problem comes partly from insufficient knowledge of urban soils, which is due to  
58 inherent difficulties for their systematic study in comparison to other soils. Because they  
59 are often developed on composite materials derived from previous uses and exogenous  
60 sources, they present a strong vertical and horizontal spatial heterogeneity: human  
61 influence leads to a great variety of soils on a limited surface area (compared to natural  
62 environments) and to a lack of spatial logic (Burghardt et al., 2015; Ajmone-Marsan et al.,  
63 2016; Levin et al., 2017). Deeply degraded soils, strongly transformed soils and pseudo-  
64 natural soils showing only little changes with respect to natural soils, may coexist in urban  
65 areas (Morel et al., 2015). In addition, urban soils are characterized by a wide range of  
66 various activities over time (Norra & Stuben, 2003) and by a very frequent and often  
67 arbitrary change of use.

68 In spite of this, the interest in urban soils has been steadily growing in the last years as  
69 a consequence of the intensification of urbanization and the increasing importance of urban  
70 environments. Urban soils are now considered an object of study *per se*, just like natural or  
71 agricultural soils, and taken into account by soil classification systems as separate groups  
72 (e.g., Anthrosols in the French reference system, Technosols in the World Reference  
73 Base for Soil Resources and, in the future, Artesols in Soil Taxonomy). As a proof of the  
74 worldwide interest of urban soils as a topic of research, specific soil surveys and extensive  
75 research programs focused on urban soils are taking place in many cities, from small and  
76 medium-sized ones like Torun or Zurich, to megalopolis like Berlin, Paris, Beijing,  
77 Moscow or New York City (Blumlein et al., 2012; Burghardt et al., 2015; Charzynski,  
78 2017; Hernandez et al., 2017; Prokof'eva & Martynenko, 2017; Shaw et al., 2018; Tresch  
79 et al., 2018; Wang et al., 2018; Quenea et al., 2019). In contrast with this extended interest,  
80 a comprehensive study of urban soils has not been yet made in any city in Spain.

81 With the objective of contributing knowledge about urban soils that is not available yet,  
82 we have performed a study of the soils of the city of Santiago de Compostela (NW Spain).  
83 The city gathers several interesting characteristics for the study of urban soils and the  
84 factors that determine their properties and functions: a high relative surface of green areas;  
85 an important geological diversity within a small area and a high diversity of land use and  
86 vegetation, including lawn areas, forested areas and urban allotment gardens. By analyzing  
87 soil surface samples from an intensive sampling in the city, we will have a comprehensive  
88 view of the properties of these soils and the factors that determine their variability, in  
89 particular the role of geology and land use.

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## MATERIAL AND METHODS

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### Study area

93 The city of Santiago de Compostela, located in the NW corner of the Iberian Peninsula,  
94 is the capital of the autonomous region of Galicia and an important political, administrative,  
95 religious and tourist center. The municipality has an an area of 222 km<sup>2</sup> and counts 97,000  
96 inhabitants. The history of the city dates back to the 9th century, but it has always been a  
97 small city (in the first decades of the 20th century it counted only 24,000 inhabitants) and  
98 does not have a high traffic intensity, with maximum intensities of only 25,000-40,000  
99 vehicles/day at certain points (Xunta de Galicia, 2012). In addition to the permanent  
100 residents, the city has over 20,000 University students and receives more than one million  
101 visitors every year. Over 30% of these visitors travel to the city for reasons related to  
102 religion or the pilgrimage route (Rodríguez et al., 2018), since Santiago de Compostela is  
103 situated at the end of the Way of Saint James, Europe's first ever pilgrimage route, dating  
104 back to the Middle Age.

105 Santiago de Compostela ranks as the third Spanish city in managed green surface per  
106 capita, with over 5,000,000 m<sup>2</sup> of managed gardens and parks, encompassing from  
107 historical gardens established in the 19th century to recently urbanized green areas  
108 established in the last decade. In the city center, there are 25 green areas with surfaces that  
109 range from 1 to 40 hectares, including lawn areas, forest areas and eight areas of urban  
110 allotment gardens; three different land uses coexist at some places in very short distances.

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### Climate

113 The city has an Oceanic climate, warm and wet, with mean annual air temperature of  
114 13.0 °C, and total mean annual precipitation of 1787 mm year<sup>-1</sup>. The relatively low values

115 for potential evapotranspiration (<300 mm in summer and 50-100 mm in winter) results in  
116 a positive water balance (600-800 mm) (Martínez Cortizas & Pérez Alberti, 1999).

117

## 118 **Geology**

119 The city is located in the contact zone between the Santiago Unit of the metamorphic  
120 massif known as the Ordes Complex and a granitic area, and therefore presents an important  
121 geological diversity (Figure 1). There are four main lithological units in the city, arranged  
122 approximately in parallel bands with a N-S direction:

123 - Santiago schists were formed during an eo-Hercynian metamorphic episode (c. 374  
124 Ma) of high-P, low- to intermediate-T. They range in composition from greywackes or  
125 semipelites, the most common, to pelites. Their texture is mainly lepidoblastic, given the  
126 predominance of mica schists over purely quartz-schistose lithologies with grano-  
127 lepidoblastic texture. However, porphyroblastic types with abundance of garnet and  
128 plagioclase porphyroblasts are frequently found (Martínez Catalán et al., 1984; Arenas et  
129 al., 1995).

130 - Orthogneisses: formed during the same high-P, low- to intermediate-T episode as  
131 Santiago schists, they are light grey, medium-grained rocks with granoblastic or  
132 blastomylonitic texture, composed by quartz, potassium feldspar, plagioclase, muscovite  
133 and biotite (Martínez Catalán et al., 1984; Díaz-García, 1990).

134 - Amphibolites: formed by retrogradation of granulites, they are dark green, fine-grained  
135 rocks with a nematoblastic texture, composed mainly of amphibole and plagioclase  
136 (Martínez Catalán et al., 1984).

137 - Granitic rocks: they are a group of Hercinian magmatic intrusions in the metamorphic  
138 units of the area, mainly medium- to coarse-grained two-mica granites with an  
139 hypidiomorphic texture, often presenting orientation due to deformation (IGME, 1981).

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### **Soil sampling**

142 Soils were sampled at 56 points (precise location is shown in Figure 1), that included  
143 soils over all geological materials and land uses present in the city (Table 1). Composite  
144 samples were obtained by mixing 4-5 subsamples taken with an auger (soil depth 0-20 cm)  
145 at each point. In addition, three undisturbed samples (0-5 cm) were taken at each point for  
146 bulk density determination using 100-cm<sup>3</sup> steel cylinders.

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### **Soil analysis**

149 Soils were air dried and passed through a 2-mm sieve before analysis. Fractions larger  
150 than 2 mm were weighed, washed with distilled water and the artifacts identified visually.  
151 For the rest of analyses, the fraction <2 mm was used. All analyses were performed by  
152 triplicate.

153 Particle size analysis was performed after organic matter destruction with H<sub>2</sub>O<sub>2</sub> and  
154 washing with 1N HCl, by dispersion with hexametaphosphate + sodium carbonate solution,  
155 followed by wet sieving for sand (>0.050 mm), and silt and clay separation by the pipette  
156 method. Soil pH was measured in water (soil:solution ratio 1:2.5), in 0.1 N KCl  
157 (soil:solution ratio 1:2.5), and in 1 N NaF solution (Fieldes & Perrott, 1966). Electrical  
158 conductivity (EC) was measured in water extracts (soil:solution ratio 1:2), following the  
159 recommendations of Pansu & Gautheyrou (2006). Exchangeable Al was determined after  
160 extraction with 2 N KCl (Bertsch & Bloom, 1996). Cation exchange capacity (CEC) and

161 exchangeable bases were determined after saturation of the soil with 1 N ammonium acetate  
162 and washing with 1 N KCl (Pansu & Gautheyrou, 2006). Exchangeable Ca, Mg, Na and K  
163 were measured in the ammonium acetate extracts by flame atomic absorption/emission  
164 spectrophotometry (Varian FS220), whereas CEC was determined by steam distillation of  
165 the ammonium displaced by the KCl solution. Available P was determined by the Olsen  
166 method, after extraction with sodium bicarbonate (Olsen & Sommers, 1982). Phosphate  
167 retention was determined after equilibration of the soil with a 1000 mg L<sup>-1</sup> phosphate  
168 solution at pH 4.6 (Blakemore et al., 1987).

169 For the study of the Fe and Al forms, selective extractant solutions were employed.  
170 Organically-complexed forms of Fe and Al (Fe<sub>p</sub> and Al<sub>p</sub>, respectively) were determined  
171 after a 16-hour extraction of 0.5 g of soil with 50 mL of 0.1 M sodium pyrophosphate at  
172 pH 10 (McKeague, 1967). Poorly-crystalline forms (Fe<sub>ox</sub> and Al<sub>ox</sub>, respectively) were  
173 determined after extraction of 0.5 g of soil with 50 mL of 0.2 M oxalic acid–ammonium  
174 oxalate at pH 3 (Schwertmann, 1991) during 4 h in the dark. Free iron (Fe<sub>DCB</sub>) was analysed  
175 after extraction with dithionite-citrate-bicarbonate solution, following the method by  
176 Mehra & Jackson (1960). All the extracts were centrifuged at 4000 g for 15 minutes and  
177 filtered through 0.45-µm filters, and Al and Fe were quantified in the extracts by flame  
178 atomic absorption spectrophotometry.

179 Finally, a fraction of sieved soil (<2 mm) was ground for total element analyses. Total  
180 C and N were analyzed in a LECO Truspec CHNS elemental analyzer. Given that the soils  
181 did not present carbonates, total C equals total organic carbon (OC) in this case.

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### Statistics

184 ANOVA mixed model analysis was used to determine the influence of parent material  
185 and land use on the properties of the soils. The normality of data was checked using the  
186 Shapiro-Wilk test. Data that did not pass the normality test were log-transformed for  
187 ANOVA. The homogeneity of variance was tested using the Levene test. When a  
188 significant effect of land use or lithology at a level of significance of  $P < 0.05$  was found,  
189 the Tukey's multiple range test was used to separate groups. Pearson's correlation analyses  
190 between all the properties analyzed were also conducted. All statistical analyses were  
191 performed using the R statistical package for MacOSX version R 3.1.3 (R Core Team,  
192 2018) and the package R Commander version 2.6-1 (Fox & Bouchet-Valat, 2019).

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## RESULTS

195 The main properties of the soils are shown in Tables 2 and 3, grouped by land use and  
196 lithology. Land use was divided in four classes: lawn, forest, urban agriculture (comprising  
197 public allotment gardens and private gardens) and periurban agriculture (the green roof soil  
198 was not used for statistics). Because of the topography of the area, soils are sometimes  
199 developed on mixtures of materials of different lithology, so we have included a  
200 "granite+schist" class of soils in addition to the schist, gneiss, granite and amphibolite  
201 classes. The tables also show the results of the ANOVA tests for assessing the effect of  
202 lithology and land use on soils properties. The whole dataset soil by soil is included in the  
203 Supplemental material (Tables S1-S2).

204 The soils present relatively low bulk densities, ranging from  $0.34$  to  $1.25 \text{ Mg m}^{-3}$  and  
205 with a mean of  $0.91 \text{ Mg m}^{-3}$ . These overall low values are due to the high organic matter  
206 contents of the soils, as shown by the strong negative correlations with OC and N (Table  
207 4). The low bulk density obtained for the green roof soil ( $0.34 \text{ Mg m}^{-3}$ ) is due to its

208 composition: a constructed soil consisting of a mixture of a peat-based substrate, sand and  
209 perlite balls. For the rest of soils, differences due to land use or lithology were not observed.  
210 It is interesting to note that the soils of recently urbanized parks present low bulk densities  
211 in comparison to historical parks, likely a reflection of a higher degree of compaction by  
212 pedestrians in the latter.

213 Most soils presented high amounts of coarse fragments (elements larger than 2 mm),  
214 mainly comprised of gravel, but also with presence of artifacts. The coarse fractions  
215 represented up to 41% of the soil weight, with a mean value of 21%: these high values can  
216 be due to the addition of coarse materials during urbanization works, but may also be a  
217 natural feature of the soils. In fact, during sampling it was observed that urban forest areas  
218 often presented soils with high stone contents and frequent rocky outcrops (although  
219 significant differences at  $P>0.05$  were not found either for lithology or land use). This is  
220 explained by the fact that forests are traditionally limited to areas with low agricultural  
221 potential, combining high slopes and shallow soils. The presence of artifacts (mostly brick  
222 and coal fragments) in the coarse fraction is generalized, although they represent in average  
223 only a 0.6% of the soil mass.

224 In general, the soils presented coarse textures (Figure 2): the dominant soil texture is  
225 sandy loam (38 soils), followed by 16 soils with loam textures. There is a significant effect  
226 of lithology on this property, with amphibolite soils with the highest clay contents and finest  
227 texture, but no differences due to land use (Table 2).

228 All the soils are rich in organic matter, with OC contents between 13 and 110 g kg<sup>-1</sup> (137  
229 g OC kg<sup>-1</sup> for the green roof soil) and total nitrogen contents ranging from 0.8 and 6.0 g  
230 kg<sup>-1</sup>. Differences due to land use or lithology were not found for OC contents, whereas for  
231 N, soils on schists present higher N contents than the soils on gneiss. The reason for this

232 difference is unclear. Regarding the C/N ratios, the values ranged from 10 to 18 (with the  
233 exception of the green roof soil, that presented a value of 38), and were higher in soils under  
234 forest vegetation, as expected. The higher value for the green roof soil is likely due to the  
235 use of peat, a material with a high C/N ratio, for its formulation. Interestingly, the properties  
236 of this constructed soil (low bulk density, high OC and C/N ratio, coarse texture, acidity)  
237 are not very different from O horizons in natural forest soils.

238 Salinity is low in all soils, as shown by the values of EC, that range from 5.4 to 28.9 mS  
239  $\text{m}^{-1}$ , with an average of 13.0 mS  $\text{m}^{-1}$ . There is a significant effect of land use, with higher  
240 EC values in soils used for urban agriculture, surely connected to high fertilization rates in  
241 these soils. No differences due to the lithology of the parent material were observed. All  
242 the soils were acid, with values of pH in water from 4.7 to 6.9 and pH in KCl ranging from  
243 3.6 to 6.1. The lower values of pH in KCl than in water indicate the presence of Al in the  
244 exchange complex, as confirmed by the strong negative correlations between exchangeable  
245 Al and pH (Table 4). The urban soils with agricultural use presented significantly higher  
246 pH values than the rest, probably due to the addition of ash and other liming materials.  
247 Significant differences due to lithology were not found in this case.

248 Cation exchange capacity (CEC) ranges from 9 to 48  $\text{cmol}_c \text{kg}^{-1}$ , with an average value  
249 of 17  $\text{cmol}_c \text{kg}^{-1}$ . Strong positive correlations were found with OC and N (Table 4),  
250 indicating the major influence of organic matter on this property. The most abundant  
251 element in the exchange complex is Ca in 46 out of 56 soils, and Al in the rest (Table S1).  
252 Neither land use nor lithology had an effect on CEC, but the composition of the exchange  
253 complex was significantly affected by land use. In this sense, agricultural soils present  
254 lower exchangeable Al and higher Ca and Mg than the rest (in line with their higher pH),  
255 whereas forests soils presented the highest amounts of exchangeable Al. Available P

256 concentrations were very variable in soils of all land uses and lithology, with values that  
257 ranged from 3 to 152 mg kg<sup>-1</sup> and an average concentration of 54 mg kg<sup>-1</sup>. Land use did  
258 not influence available P concentrations, but a significant effect of lithology was found,  
259 with the soils on gneiss as the richest in available P; as happened for N, we do not have an  
260 explanation for this fact. The fact that all soils developed on gneiss are located in the middle  
261 of the city (Figure 1) might be suggesting that high P concentrations are connected to a  
262 higher level of pollution in these soils because of their location.

263 The results of the selective extractions of Fe and Al and related properties are shown in  
264 Table 3. Free iron contents (Fe<sub>DCB</sub>) reach a maximum of 45 g kg<sup>-1</sup>, with the highest amounts  
265 in the amphibolite soils and lower concentrations in the granite and gneiss soils, in  
266 agreement with the mineralogical composition of each rock. In this sense, Fe<sub>DCB</sub> was  
267 positively correlated with clay content, that was also higher in amphibolite soils. The  
268 concentrations of Fe and Al extracted in oxalate (1.6-9.6 g kg<sup>-1</sup> for Fe and 1.0-11.9 g kg<sup>-1</sup>  
269 for Al) are indicative of important amounts of poorly crystalline phases in all the soils, an  
270 important part of which correspond to organo-metal associations (0.7-6.9 g kg<sup>-1</sup> for Fe<sub>p</sub> and  
271 0.6-7.2 g kg<sup>-1</sup> for Al<sub>p</sub>). Fe<sub>ox</sub> was significantly affected by lithology, but not Al<sub>ox</sub>, whereas  
272 no significant effect of land use or lithology was observed neither on Fe<sub>p</sub> nor Al<sub>p</sub>. Both  
273 elements were positively correlated to OC and N, showing the association of these  
274 compounds and soil organic matter.

275 The sum of Al<sub>ox</sub>+1/2Fe<sub>ox</sub> is a diagnostic criterion employed to identify andic properties  
276 in soil classification systems including Soil Taxonomy and the World Reference Base for  
277 Soil Resources. None of the soils would fulfil the criterion for andic properties (Al<sub>ox</sub>+1/2Fe<sub>ox</sub>  
278 >2%), but two of them do it for protoandic properties (Al<sub>ox</sub>+1/2Fe<sub>ox</sub> >1.2%). The presence  
279 of allophane and/or poorly-crystalline organo-aluminium complexes is indicated by pH<sub>NaF</sub>

280 values  $\geq 9.5$ , which were observed in 16 out of 56 soils, in all parent materials and land  
281 uses, and it was positively correlated to all forms of extractable Al. All the soils presented  
282 important phosphate retention, also indicative of the presence of poorly crystalline Fe and  
283 Al forms, with values ranging from 15 to 89%, but only one soil (soil 6, under *Quercus*  
284 vegetation) reached the 85% retention required for defining andic properties. This soil also  
285 presented the highest  $\text{pH}_{\text{NaF}}$  and  $\text{Al}_{\text{ox}} + \frac{1}{2}\text{Fe}_{\text{ox}}$  values (Table S2), showing that its properties  
286 might be close to those of Andosols.

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## DISCUSSION

289 The urban soils studied here present a series of properties that make them closer to non-  
290 urban soils in the region than to typical urban soils. Galician soils are acid as a result of the  
291 high rainfall regime and the predominance of acid igneous and metamorphic rocks, with  
292 almost complete absence of calcareous materials. High water availability throughout the  
293 year and warm temperatures result in a high plant productivity, with large returns of plant  
294 inputs to soil, producing important accumulation of organic matter in the soils. As a result  
295 of the combination of acidity, high organic matter contents and low degree of development,  
296 Umbrisols (Dystrudepts in Soil Taxonomy) are the dominant soils in the region. In the  
297 Santiago area, soils in non-urban areas are classified as Cambisols and Umbrisols (on all  
298 parent materials), with presence of Andosols on amphibolites (Calvo de Anta & Macías  
299 Vázquez, 2002).

300 Almost all urban soils studied in this work presented high OC and N contents, similar to  
301 natural and agricultural soils in the region, for which the most common interval of variation  
302 ranges between 3-4% OC and 0.2-0.3% N (Calvo de Anta et al., 2015). The predominantly  
303 sandy-loam textures and the amounts of coarse material (20-30%), as well as the

304 differences observed due to lithology of the parent material, are also consistent with the  
305 properties of natural and agricultural soils of the region. The heavier texture of soils over  
306 amphibolites is common in the Galician region, where it has been reported that granite soils  
307 usually present sandy-loam textures, soils on biotite schists are sandy-loam to loam,  
308 whereas soils developed on amphibolites present mostly loam to clay-loam textures (Calvo  
309 de Anta et al., 1992).

310 Another coincidence with Galician non-urban soils is the fact that all soils are acid and  
311 have an important presence of Al in the exchange complex. Among land uses, pH is higher  
312 in urban garden soils (although neutrality was not reached in any soil), likely because of  
313 agricultural gardening practices involving addition of ashes and other liming materials.  
314 Fertilization and amendment are also the reason why these soils presented higher salinity  
315 and plant nutrient contents (P, Ca and Mg, although in the case of P, high concentrations  
316 were found for all land uses so its presence is probably not exclusively linked to  
317 fertilization). In this sense, it is interesting to note that some properties related to  
318 fertilization, including pH, salinity, Ca and Mg contents, were higher in urban gardens than  
319 in periurban agricultural soils. This might be the result of a more intensive management in  
320 the urban gardens, in particular higher fertilization rates and application of garden compost  
321 and domestic ashes (Burghardt & Schneider, 2018; Burghardt et al., 2018). This agrees  
322 with observations by other authors in the sense that yields in urban gardens are much higher  
323 than in commercial vegetable farms because of the high intensity of material and labor  
324 resources in the first (McDougal et al., 2019).

325 The significant presence of poorly-crystalline mineral phases in all urban soils studied,  
326 as evidenced by the values of  $\text{pH}_{\text{NaF}}$ , phosphate retention and oxalate-extractable Fe and  
327 Al, is another property that connect them to natural soils. Under the climatic conditions of

328 the region, rocks rich in weatherable minerals (specially gabbros, amphibolites and  
329 serpentinites, but also biotite schists) produce soils with significant amounts of poorly  
330 crystalline mineral constituents and organo-metal complexes (García-Rodeja et al., 1987).  
331 This leads to soils with andic properties (IUSS-WRB, 2014) that are even classified as  
332 Andosols in some cases (García Rodeja et al., 1987; Verde et al., 2005). In the soils studied  
333 here, however, this andic character is weak with respect to their natural counterparts, and  
334 although it happens for all parent materials and land uses, it is more strongly expressed in  
335 soils over schists and amphibolites and under forest vegetation. In any case, the criteria  
336 needed for andic properties is not fulfilled by any soil. This attenuation of the andic  
337 character of anthropized soils due to agricultural use and/or a different soil management  
338 has been reported in the literature for cultivated versus forest or shrubland soils (Verde et  
339 al., 2005; Ferro-Vázquez et al., 2014; Arias et al., 2016; Paradelo et al., 2016). Our data  
340 show that urbanization also leads to a loss of this andic character, either because city growth  
341 proceeds in former agricultural soils that had already lost their andic character, or because  
342 of mixing of the original soils with subsoil or other materials during construction and  
343 urbanization.

344 In summary, it is obvious that, despite whatever differences due to lithology or land use,  
345 the whole properties of the soils fall within what is expected in the natural soils of the area,  
346 in contrast with is regarded as typical of urban soils. Urban soils in other areas of the world  
347 usually exhibit features radically different to those of natural soils, in particular high bulk  
348 density, alkaline pH and important presence of artifacts and residues from human activities  
349 (Burghardt et al., 2015). The most obvious difference of the soils of Santiago de  
350 Compostela with other urban soils is their acidity: the high pH typical of urban soils due to  
351 the presence of mortar and other carbonate materials has not been observed here. Besides,

352 urban soils have been reported to present high amounts of coarse material and/or artifacts  
353 (Howard, 2017), but in the soils of Santiago they are not very abundant: although artifacts  
354 are present in all soils and therefore allow to identify them as unequivocally urban, they  
355 represent in average only a 0.6% of the soil mass. This would be indicative of a low degree  
356 of artificialization that would frame most of these soils (in particular the urban gardens and  
357 forest soils) within the “Pseudo-natural soils” group in the categorization by Morel et al.  
358 (2015), reserved to anthropic soils with little changes compared to corresponding natural  
359 soils. Similarly to natural or agricultural soils, these soils and the ecosystems developed on  
360 them are capable of providing a wider range of ecosystem services than severely impacted  
361 soils, in particular regarding provisioning services (food production and support for  
362 vegetation, among others) and regulating services such as water storage or runoff and flood  
363 control (Morel et al., 2015). In this sense, the presence of these soils is very positive and  
364 their preservation is essential for urban ecosystems.

365 Our work shows that the soils of Santiago de Compostela have been well-preserved from  
366 the impacts that often come with urbanization, despite the long history of anthropic  
367 influence in this city, that dates back to the Middle Age. This points to a low pressure that  
368 is the result of a combination of local and regional factors. First, the city has never been  
369 destroyed by a war (as is the case in many European cities) or natural disasters, so it has  
370 not been subjected to large reconstruction projects. Second, the societal transformations  
371 that lead to the intensification of urbanization have been slow and not very intense in  
372 Galicia: the significant urban growth that happened in other European regions during the  
373 19<sup>th</sup> century did not occur in Galicia until the 1970s. In addition, the low industrial  
374 development of Santiago, that evolved as an administrative, political, educational and  
375 religious center rather than as an industrial city, produced an additional delay in urban

376 expansion in comparison to other cities in the region (Fernández-Maldonado et al., 2016).  
377 Finally, the inclusion of the city in the UNESCO World Heritage List in 1985 has  
378 undoubtedly played an indirect yet very important role in the limitation of the impacts of  
379 urbanization on soils, by stimulating the maintenance of Santiago's compact urban fabric  
380 against uncontrolled urban expansion. The influence, either direct or indirect, that urban  
381 planning choices have had on the properties of urban soils in Santiago de Compostela is an  
382 important lesson for soil preservation in our cities.

383

384

### CONCLUSIONS

385 The soils of the city of Santiago de Compostela (NW Spain) are acid, coarse-textured  
386 and rich in organic matter, with differences in soil composition and chemical properties due  
387 to diversity of parent material and land use. Soils developed over amphibolites present  
388 heavier textures, higher amounts of Fe compounds and phosphate retention than soils  
389 developed over schist, gneiss or granite. Among land uses, soils of urban allotments  
390 gardens presented higher nutrient contents, pH and salinity than soils under forest or lawn  
391 vegetation. In general, the soils studied here do not present typical features of urban soils  
392 in other cities and they are more similar to natural and agricultural soils of the region than  
393 to other urban soils. This is the result of a combination of socioeconomical factors that have  
394 reduced the impact of urbanization with respect to other cities. Preservation of these  
395 "pseudo-natural" soils is essential for the city because of the wide range of ecosystem  
396 services that they can provide, in comparison to soils that have been more impacted by  
397 urbanization.

398

399

### ACKNOWLEDGEMENTS

400 The authors gratefully acknowledge the support of the City Hall of Santiago de  
401 Compostela for this study. Dr. Paradelo thanks the Spanish Ministry of Economy and  
402 Competitiveness (MINECO) for his *Ramón y Cajal* fellowship (RYC-2016-19286). This  
403 research has been funded by the Xunta de Galicia regional government (grant number  
404 ED431F 2018/04). We gratefully thank three anonymous reviewers who provided very  
405 constructive and insightful comments.

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407

### SUPPLEMENTAL MATERIAL

408 Supplemental material contains two tables. Supplemental Table S1 shows the general  
409 characterization of each soil used in this study. Supplemental Table S2 shows the results of  
410 the Fe and Al extractions for each soil.

411

412

### CONFLICT OF INTEREST STATEMENT

413 The authors declare no conflict of interest.

414

415

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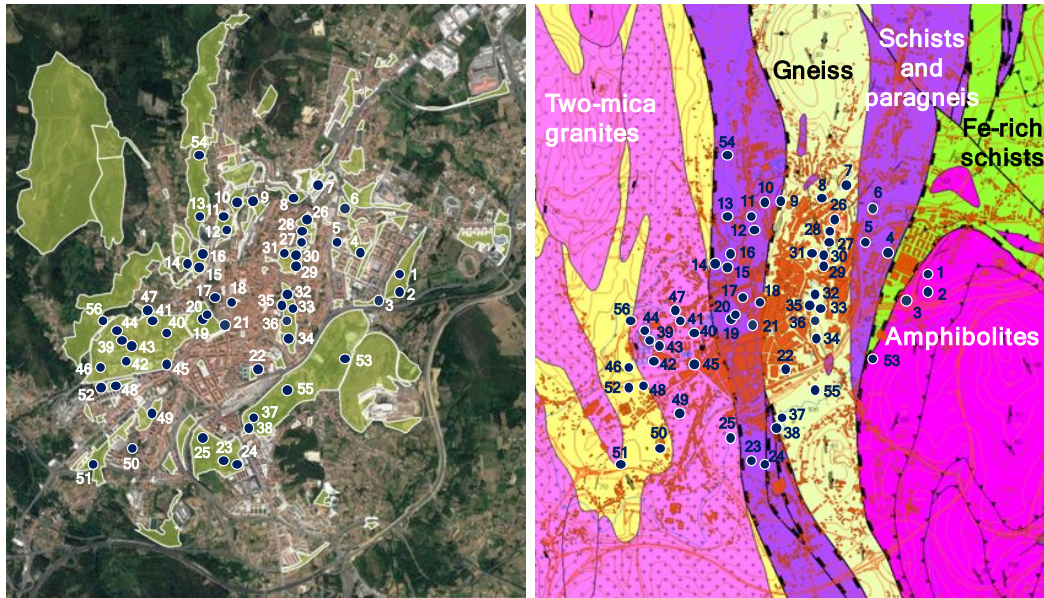
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FIGURES AND TABLES

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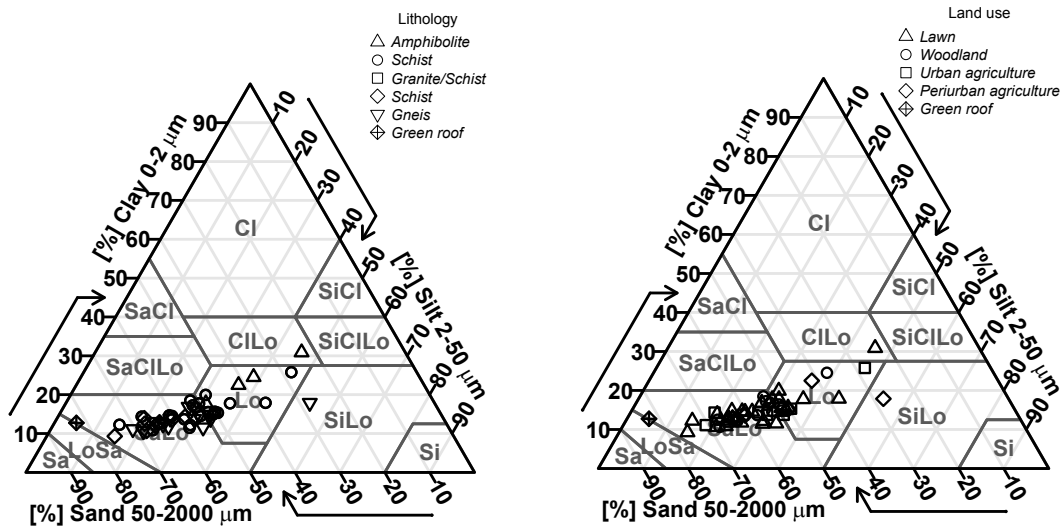


550

551 Figure 1. Study area, geology and location of sampling points.

552

553



554

555 Figure 2. Soil texture as a function of land use and lithology. Plots were drawn using the  
556 *soiltexture* package for R (Moeys, 2014).

557

558 Table 1. List of sampling points.

Name	Longitude	Latitude	Lithology	Color (dry)	Land use
1 Carlomagno 1	42.8832	-8.5231	Amphibolite	10YR 5/6	Lawn
2 Carlomagno 2	42.8810	-8.5242	Amphibolite	10YR 4/4	Woodland ( <i>Quercus robur</i> )
3 Vieiro	42.8795	-8.5273	Amphibolite	10YR 4/4	Lawn
4 Fontiñas 1	42.8839	-8.5301	Schist	10YR 4/3	Lawn
5 Fontiñas 2	42.8847	-8.5324	Schist	10YR 3/2	Allotment garden
6 Monte dos Postes	42.8880	-8.5315	Schist	10YR 3/3	Lawn
7 San Cactano	42.8899	-8.5348	Schist	10YR 4/3	Lawn
8 Bouza Brey	42.8890	-8.5390	Schist	2.5Y 5/3	Lawn
9 Burgo Xixón	42.8883	-8.5429	Schist	10YR 5/3	Lawn
10 Auditorio	42.8883	-8.5447	Schist	10YR 5/3	Lawn
11 Vistalegre 1	42.8872	-8.5469	Schist	10YR 5/4	Woodland ( <i>Quercus robur</i> )
12 Vistalegre 2	42.8857	-8.5460	Schist	2.5Y 5/3	Lawn
13 Santa Isabel	42.8870	-8.5497	Schist	10YR 5/3	Private garden
14 Espiño	42.8832	-8.5517	Schist	10YR 3/4	Woodland ( <i>Quercus robur</i> , <i>Ilex aquifolium</i> )
15 Galeras 1	42.8823	-8.5499	Schist	10YR 5/3	Lawn
16 Galeras 2	42.8834	-8.5495	Schist	2.5Y 5/3	Lawn
17 Campo das Hortas	42.8799	-8.5477	Schist	10YR 4/2	Allotment garden
18 Fonseca	42.8792	-8.5458	Schist	10YR 4/3	Lawn
19 Alameda 1	42.8779	-8.5494	Schist	10YR 5/3	Lawn
20 Alameda 2	42.8784	-8.5493	Schist	10YR 4/3	Woodland ( <i>Quercus robur</i> )
21 Alameda 3	42.8774	-8.5465	Schist	2.5Y 5/3	Lawn
22 Parlamento	42.8733	-8.5422	Schist	10YR 4/4	Lawn
23 Granell 1	42.8649	-8.5466	Schist	10YR 4/3	Lawn
24 Granell 2	42.8641	-8.5448	Schist	10YR 4/3	Woodland ( <i>Acacia melanoxylon</i> )
25 Granell 3	42.8665	-8.5491	Granite/Schist	10YR 3/3	Woodland ( <i>Quercus robur</i> )
26 Almaciga 3	42.8864	-8.5364	Schist	10YR 4/3	Lawn
27 Almaciga 1	42.8850	-8.5371	Gneiss	10YR 6/3	Lawn
28 Almaciga 2	42.8856	-8.5371	Gneiss	2.5Y 4.5/3	Allotment garden
29 Bonaval 1	42.8827	-8.5378	Gneiss	10YR 6/3	Lawn
30 Bonaval 2	42.8837	-8.5380	Gneiss	10YR 4/2	Woodland ( <i>Quercus robur</i> )
31 Caramoniña	42.8842	-8.5390	Gneiss	10YR 5/2	Allotment garden
32 Belvis 1	42.8798	-8.5384	Gneiss	10YR 6/3	Lawn
33 Belvis 2	42.8794	-8.5381	Gneiss	10YR 5/3	Allotment garden
34 Belvis 3	42.8759	-8.5389	Gneiss	10YR 5/3	Woodland (mixed ornamental species)
35 Belvis 4	42.8800	-8.5390	Gneiss	10YR 4/2	Allotment garden
36 Belvis 5	42.8777	-8.5390	Gneiss	2.5Y 5/3	Lawn
37 Paxonal 1	42.8685	-8.5434	Gneiss	2.5Y 5/3	Lawn
38 Paxonal 2	42.8681	-8.5437	Gneiss	2.5Y 5/3	Allotment garden
39 Campus 1	42.8761	-8.5587	Granite	10YR 5/3	Lawn
40 Campus 2	42.8766	-8.5541	Granite/Schist	10YR 5/4	Lawn
41 Campus 3	42.8780	-8.5561	Granite/Schist	10YR 5/3	Woodland ( <i>Quercus robur</i> )
42 Campus 4	42.8739	-8.5589	Granite/Schist	10YR 4/3	Woodland (mixed ornamental species)
43 Campus 5	42.8754	-8.5585	Granite	10YR 5/4	Woodland ( <i>Acacia melanoxylon</i> )
44 Campus 6	42.8768	-8.5595	Granite/Schist	10YR 4/3	Lawn
45 Campus 7	42.8738	-8.5541	Granite/Schist	10YR 4/3	Lawn
46 Campus 8	42.8732	-8.5624	Granite	2.5Y 5/3	Woodland (riparian species)
47 San Lourenzo	42.8783	-8.5565	Granite/Schist	10YR 5/3	Woodland ( <i>Quercus robur</i> )
48 Barcelona	42.8717	-8.5604	Granite	2.5Y 5/3	Lawn
49 Santa Marta 1	42.8689	-8.5558	Granite	10YR 5/3	Lawn
50 Santa Marta 2	42.8658	-8.5583	Granite	10YR 5/3	Private garden
51 Santa Marta 3	42.8646	-8.5632	Granite	10YR 5/2	Allotment garden
52 CEBEGA	42.8714	-8.5618	-	10YR 2/1	Green roof
53 Multiusos	42.8744	-8.5308	Amphibolite	10YR 4/4	Agriculture
54 Lermo	42.8925	-8.5501	Schist	10YR 4/3	Agriculture
55 Brañas	42.8713	-8.5389	Gneiss	2.5Y 5/3	Agriculture
56 Botánico	42.8774	-8.5617	Granite	10YR 4/3	Agriculture

559

560 **Table 2. General soil characterization and results of ANOVA for the effect of land use and lithology on each property. Significance**  
 561 **of the effect of factors is indicated as follows: \* significant at a P-value of 0.05; \*\* significant at a P-value of 0.01; \*\*\* significant at**  
 562 **a P-value of 0.001. Data for the green roof soil were not included in the statistics.**

			Bulk density	Gravel	Artifacts	Clay	EC	pH <sub>w</sub>	pH <sub>k</sub>	OC	N	C/N	Available P	CEC	Al ex	Ca ex	Mg ex	Na ex	K ex
			(Mg m <sup>-3</sup> )	(%)	(g kg <sup>-1</sup> )	(g kg <sup>-1</sup> )	(mS m <sup>-1</sup> )			(g kg <sup>-1</sup> )	(g kg <sup>-1</sup> )		(mg kg <sup>-1</sup> )		----- (cmol <sub>c</sub> kg <sup>-1</sup> ) -----				
Land use	Lawn n = 28	Minimum	0.57	6	0.2	93	5.4	5.0	3.8	13	0.8	10	3	9	0.1	0.0	0.1	0.1	0.1
		Maximum	1.19	38	51.1	309	20.3	6.3	5.2	70	5.4	17	152	22	1.8	6.4	1.4	0.5	0.8
		Mean	0.90	23	5.7	149	11.5	5.6	4.3	33	2.6	13	50	16	0.7	2.7	0.6	0.2	0.5
		SD	0.15	7	10.4	41	4.1	0.3	0.4	12	0.9	1	37	3	0.6	1.6	0.3	0.1	0.2
	Woodland n = 13	Minimum	0.46	12	0.1	107	6.0	4.7	3.6	21	1.3	13	5	11	0.2	0.3	0.1	0.1	0.3
		Maximum	1.25	41	56.2	245	28.3	6.5	5.7	110	6.0	18	122	36	4.1	20.1	1.3	0.5	0.9
		Mean	0.92	23	10.0	150	12.1	5.4	4.2	44	2.9	15	49	19	1.4	3.6	0.6	0.2	0.7
		SD	0.26	8	18.0	37	5.7	0.5	0.6	24	1.3	2	41	7	1.4	5.2	0.4	0.1	0.2
	Urban agriculture n = 10	Minimum	0.75	9	0.5	111	7.1	5.6	4.3	21	1.4	10	25	12	0.0	3.0	0.5	0.1	0.6
		Maximum	1.24	28	12.0	258	28.9	6.9	6.1	49	4.7	15	127	31	0.3	11.9	1.6	0.6	1.3
		Mean	1.01	17	5.5	149	18.0	6.2	5.2	34	2.6	13	72	19	0.1	7.7	1.0	0.2	1.0
		SD	0.14	7	4.4	40	6.6	0.4	0.5	10	1.0	1	40	7	0.1	3.2	0.4	0.2	0.2
	Periurban agriculture n = 4	Minimum	0.72	1	0.3	136	9.2	5.5	4.2	34	2.6	12	14	16	0.2	3.7	0.6	0.1	0.2
		Maximum	1.10	24	9.6	225	13.2	6.3	5.2	41	3.2	14	143	20	0.3	6.5	0.9	0.1	0.8
		Mean	0.90	15	3.4	173	11.1	5.9	4.7	37	2.9	13	65	17	0.2	5.0	0.8	0.1	0.6
		SD	0.16	10	4.3	39	1.8	0.4	0.4	3	0.3	1	57	2	0.1	1.2	0.1	0.0	0.3
Green roof n = 1			0.34	30	1.0	127	23.6	6.1	5.0	137	3.5	39	13	48	0.2	18.4	8.0	0.4	1.5
Lithology	Amphibolite n = 4	Minimum	0.87	6	0.3	178	5.4	5.4	4.4	23	1.9	12	8	16	0.2	1.4	0.4	0.1	0.3
		Maximum	1.18	25	1.9	309	16.4	6.3	5.2	40	2.9	14	40	20	0.7	4.9	1.1	0.2	0.8
		Mean	0.96	15	1.1	239	11.0	5.8	4.6	33	2.5	13	24	17	0.4	3.2	0.8	0.1	0.5
		SD	0.15	8	0.8	54	4.8	0.4	0.4	7	0.4	1	16	2	0.2	1.4	0.3	0.0	0.3

			Bulk density (Mg m <sup>-3</sup> )	Gravel (%)	Artifacts (g kg <sup>-1</sup> )	Clay (g kg <sup>-1</sup> )	EC (mS m <sup>-1</sup> )	pH <sub>w</sub>	pH <sub>k</sub>	OC (g kg <sup>-1</sup> )	N (g kg <sup>-1</sup> )	C/N	Available P (mg kg <sup>-1</sup> )	CEC	Al ex	Ca ex	Mg ex	Na ex	K ex
			----- (cmol <sub>c</sub> kg <sup>-1</sup> ) -----																
Schist n = 23	Minimum	0.46	9	0.1	109	5.5	4.7	3.8	20	1.8	10	4	12	0.0	0.3	0.2	0.1	0.1	
	Maximum	1.16	38	56.2	258	28.3	6.5	5.7	70	5.4	16	116	31	3.5	20.1	1.6	0.6	1.3	
	Mean	0.90	23	8.7	156	12.8	5.6	4.4	40	3.1	13	56	19	0.8	4.3	0.8	0.3	0.6	
	SD	0.17	8	15.3	32	4.9	0.5	0.5	13	0.9	1	34	5	0.9	4.6	0.4	0.2	0.3	
Gneiss n = 13	Minimum	0.67	1	0.4	106	6.9	4.8	3.6	13	0.8	11	8	9	0.1	0.7	0.3	0.1	0.2	
	Maximum	1.25	28	42.5	179	28.9	6.9	6.1	50	3.6	16	152	23	3.2	11.3	1.5	0.2	1.3	
	Mean	0.97	19	7.0	135	16.3	5.9	4.7	29	2.2	13	91	15	0.5	5.3	0.8	0.1	0.7	
	SD	0.20	8	11.2	22	6.9	0.6	0.7	10	0.8	1	42	4	0.9	3.2	0.3	0.0	0.3	
Granite + schist n = 7	Minimum	0.54	13	1.1	121	8.0	4.8	3.6	25	1.7	13	10	13	0.2	0.8	0.3	0.1	0.3	
	Maximum	1.15	28	13.4	168	12.3	5.8	4.6	110	6.0	18	108	36	4.1	4.4	1.1	0.2	0.8	
	Mean	0.92	21	3.9	143	9.3	5.4	4.1	44	2.8	15	35	20	1.3	2.6	0.6	0.1	0.6	
	SD	0.21	6	4.3	19	1.5	0.4	0.3	30	1.5	2	34	8	1.3	1.3	0.3	0.0	0.2	
Granite n = 8	Minimum	0.66	11	0.4	93	6.0	5.0	4.0	21	1.3	13	3	11	0.0	0.0	0.1	0.1	0.3	
	Maximum	1.15	41	15.4	144	17.4	6.4	5.3	45	3.4	17	43	18	1.7	4.9	0.9	0.1	1.0	
	Mean	0.92	23	4.3	124	11.0	5.6	4.4	30	2.2	14	24	14	0.5	2.8	0.5	0.1	0.7	
	SD	0.17	10	4.9	17	4.4	0.5	0.4	9	0.8	2	12	2	0.5	1.8	0.3	0.0	0.2	
Statistics	Land use	F	0.86	2.39	0.41	0.58	3.6	10.5	10	1.42	0.37	6.3	0.91	2.7	10.8	5.1	4.3	1.38	14
		p	0.47	0.08	0.75	0.63	0.02*	<0.001***	<0.001***	0.25	0.78	<0.001***	0.44	0.06	<0.001***	0.004**	0.009**	0.26	<0.001***
	Lithology	F	0.37	1.30	0.74	10.5	2.39	1.51	1.59	2.41	3.3	2.87	7.1	1.73	1.27	1.3	1.4	8.9	0.455
		p	0.83	0.28	0.57	<0.001***	0.06	0.21	0.19	0.06	0.02*	0.03*	<0.001***	0.16	0.29	0.28	0.25	<0.001***	0.77
	Interaction	F	0.64	1.42	0.62	0.38	0.8	0.51	0.48	0.41	0.45	0.41	0.56	0.35	1.08	0.40	0.77	1.13	0.82
		p	0.75	0.21	0.77	0.94	0.62	0.86	0.88	0.92	0.90	0.92	0.82	0.95	0.4	0.93	0.65	0.36	0.6

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564

565 **Table 3. Fe and Al selective extractions and related properties of the soils and results**  
 566 **of ANOVA for the effect of land use and lithology on each property. Significance of**  
 567 **the effect of factors is indicated as follows: \* significant at a P-value of 0.05; \*\***  
 568 **significant at a P-value of 0.01; \*\*\* significant at a P-value of 0.001. Data for the green**  
 569 **roof soil were not included in the statistics.**

			pH <sub>NaF</sub>	P retention (%)	Fe <sub>DCB</sub> (g kg <sup>-1</sup> )	Fe <sub>ox</sub> (g kg <sup>-1</sup> )	Fe <sub>p</sub> (g kg <sup>-1</sup> )	Al <sub>ox</sub> (g kg <sup>-1</sup> )	Al <sub>p</sub> (g kg <sup>-1</sup> )	Al <sub>ox</sub> + ½Fe <sub>ox</sub> (g 100 g <sup>-1</sup> )	
Land use	Lawn n = 28	Minimum	8.0	18	6	2.9	1.2	1.7	0.9	0.3	
		Maximum	10.9	89	42	9.1	4.7	11.9	7.1	1.6	
		Mean	9.1	41	14	4.5	2.6	4.0	2.8	0.6	
		SD	0.7	16	8	1.6	0.9	2.3	1.4	0.3	
	Woodland n = 13	Minimum	7.8	26	7	1.6	0.9	1.6	1.3	0.2	
		Maximum	10.5	77	33	6.4	6.9	7.3	7.2	1.1	
		Mean	9.0	41	13	4.0	2.8	3.6	3.1	0.6	
		SD	0.7	16	7	1.4	1.5	1.5	1.6	0.2	
	Urban agriculture n = 10	Minimum	8.8	15	6	2.8	1.3	1.3	1.1	0.3	
		Maximum	10.3	61	19	9.6	5.6	6.4	5.2	1.1	
		Mean	9.6	29	10	4.3	2.6	3.7	2.8	0.6	
		SD	0.5	12	4	1.9	1.2	1.4	1.3	0.2	
	Periurban agriculture n = 4	Minimum	8.7	17	12	2.2	1.9	2.0	2.0	0.3	
		Maximum	9.9	43	45	6.9	6.0	4.7	3.7	0.8	
		Mean	9.3	25	22	5.0	3.4	3.9	3.1	0.6	
		SD	0.5	12	16	2.0	1.9	1.3	0.8	0.2	
	Green roof n = 1			7.5	19	2	2.1	0.7	1.0	0.6	0.2
	Lithology	Amphibolite n = 4	Minimum	8.7	41	31	4.7	1.9	4.0	1.4	0.6
			Maximum	9.2	58	45	9.1	3.2	5.5	4.1	1.0
			Mean	9.0	49	38	6.0	2.6	4.7	2.9	0.8
SD			0.2	9	7	2.1	0.6	0.6	1.1	0.2	
Schist n = 23		Minimum	8.0	15	7	2.8	1.2	1.7	1.3	0.4	
		Maximum	10.9	89	24	9.6	6.9	11.9	7.2	1.6	
		Mean	9.2	41	15	4.9	3.2	4.4	3.3	0.7	
		SD	0.8	19	5	1.8	1.4	2.5	1.7	0.3	
Gneiss n = 13		Minimum	8.2	18	6	2.8	1.3	1.3	0.9	0.3	
		Maximum	9.6	41	15	6.9	6.0	4.5	3.7	0.8	
		Mean	9.0	28	10	3.9	2.4	3.0	2.2	0.5	
		SD	0.4	7	2	1.0	1.2	0.9	0.8	0.1	
Granite + schist n = 7		Minimum	8.3	26	8	2.1	1.1	2.2	1.5	0.3	
		Maximum	10.8	64	13	5.3	4.0	6.3	5.1	0.8	
		Mean	9.3	43	11	4.0	2.5	4.1	3.3	0.6	
		SD	0.8	16	2	1.0	0.9	1.4	1.3	0.2	
Granite n = 8		Minimum	7.8	17	6	1.6	0.9	1.6	1.3	0.2	
		Maximum	10.6	57	12	3.8	3.0	4.8	3.8	0.6	
		Mean	9.6	33	9	2.9	2.0	3.2	2.6	0.5	
		SD	0.9	12	2	0.7	0.6	1.0	0.8	0.1	
Statistics	Land use	F	1.56	3.87	2.24	0.55	0.44	0.09	0.25	0.24	
		p	0.21	0.014*	0.09	0.65	0.73	0.96	0.86	0.87	
	Lithology	F	0.92	2.85	21.1	5.6	2.21	1.97	1.27	2.8	
		p	0.46	0.03*	<0.001***	<0.001***	0.08	0.11	0.29	0.035*	
	Interaction	F	0.92	0.42	0.26	0.89	1.35	0.61	0.56	0.67	
		p	0.52	0.92	0.98	0.54	0.25	0.78	0.82	0.73	

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571 **Table 4. Correlation matrix for selected properties of the soils. Significance of correlation is indicated as follows: \* significant at a**  
 572 **P-value of 0.05; \*\* significant at a P-value of 0.01; \*\*\* significant at a P-value of 0.001. Data for the green roof soil were not included**  
 573 **in the calculations.**

	Bulk density	Gravel	Artifacts	Clay	EC	pHw	pHk	OC	N	C/N	Available P	CEC	Al ex	Ca ex	Mg ex	Na ex	K ex	pH <sub>NaF</sub>	Phosphate retention	Fe <sub>DCB</sub>	Fe <sub>ox</sub>	Al <sub>ox</sub>	Fe <sub>p</sub>	Al <sub>p</sub>
Bulk density	1																							
Gravel	0.19	1																						
Artifacts	0.24	0.32*	1																					
Clay	-0.12	-0.53***	-0.19	1																				
EC	-0.13	0.02	0.17	-0.01	1																			
pHw	0.41**	-0.14	0.22	0.09	0.44***	1																		
pHk	0.35**	-0.13	0.26	0.04	0.55***	0.95***	1																	
OC	-0.51***	-0.10	0.05	0.28*	0.19	-0.24	-0.16	1																
N	-0.53***	-0.10	0.03	0.38**	0.21	-0.20	-0.13	0.93***	1															
C/N	-0.02	-0.08	0.09	-0.14	-0.00	-0.10	-0.04	0.29*	-0.03	1														
Available P	0.16	-0.08	0.26	-0.13	0.33*	0.18	0.16	-0.17	-0.09	-0.27**	1													
CEC	-0.37**	-0.19	0.06	0.32*	0.43***	0.003	0.06	0.84***	0.79***	0.27*	-0.03	1												
Al ex	-0.52***	0.06	-0.22	-0.03	-0.24	-0.75***	-0.66***	0.54***	0.40**	0.36**	-0.21	0.33*	1											
Ca ex	0.26	-0.03	0.46***	0.04	0.74***	0.76***	0.81***	0.09	0.12	-0.004	0.34*	0.39**	-0.51***	1										
Mg ex	0.06	-0.12	0.24	0.20	0.64***	0.58***	0.54***	0.23	0.27*	-0.09	0.21	0.49***	-0.43**	0.70***	1									
Na ex	-0.15	-0.16	-0.03	0.29*	0.23	0.13	0.13	0.26	0.40**	-0.29*	0.13	0.49***	0.05	0.28*	0.29*	1								
K ex	0.17	-0.03	0.12	-0.01	0.56***	0.59***	0.53***	0.10	0.10	0.09	0.19	0.43**	-0.34	0.63***	0.63***	0.26	1							
pH <sub>NaF</sub>	0.06	-0.42**	-0.28*	0.17	-0.21	0.17	0.17	0.01	0.02	0.16	-0.31*	0.05	-0.09	-0.05	-0.15	0.12	0.03	1						
P retention	-0.39**	-0.13	-0.28*	0.42**	-0.22	-0.32*	-0.29*	0.55***	0.51***	0.23	-0.54***	0.33*	0.45***	-0.38**	-0.18	0.09	-0.28*	0.38**	1					
Fe <sub>DCB</sub>	-0.10	-0.27	-0.24	0.82***	-0.09	0.04	0.006	0.12	0.20	-0.14	-0.28*	0.11	-0.03	-0.12	0.07	0.09	-0.14	0.02	0.42**	1				
Fe <sub>ox</sub>	-0.24	-0.54***	-0.23	0.80***	-0.02	0.04	0.006	0.38**	0.53***	-0.25	-0.01	0.36**	0.05	0.004	0.15	0.43**	-0.05	0.26	0.47***	0.59***	1			
Al <sub>ox</sub>	-0.25	-0.41**	-0.31*	0.52***	-0.19	-0.06	-0.04	0.50***	0.57***	0.003	-0.28*	0.37**	0.18	-0.16	-0.07	0.33*	-0.11	0.63***	0.77***	0.40**	0.72***	1		
Fe <sub>p</sub>	-0.45***	-0.50***	-0.24	0.54***	-0.11	-0.22	-0.23	0.53***	0.63***	-0.14	0.01	0.44***	0.36**	-0.13	-0.03	0.44***	-0.11	0.33*	0.48***	0.29*	0.78***	0.67***	1	
Al <sub>p</sub>	-0.33*	-0.31*	-0.32*	0.34*	-0.27*	-0.27*	-0.23	0.58***	0.60***	0.09	-0.24	0.41**	0.44***	-0.27*	-0.22	0.29*	-0.15	0.57***	0.72***	0.21	0.55***	0.86***	0.76***	1
Al <sub>ox</sub> +½Fe <sub>ox</sub>	-0.26	-0.48***	-0.30*	0.65***	-0.14	-0.04	-0.03	0.49***	0.59***	-0.08	-0.21	0.39**	0.15	-0.12	-0.01	0.38**	-0.10	0.56***	0.72***	0.49***	0.86***	0.97***	0.75***	0.81***

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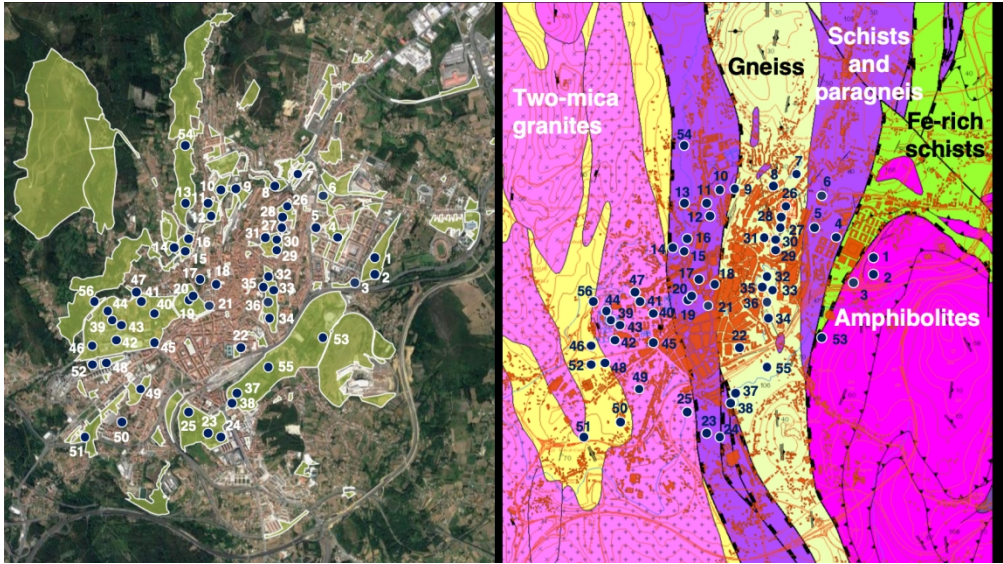


Figure 1. Study area, geology and location of sampling points.

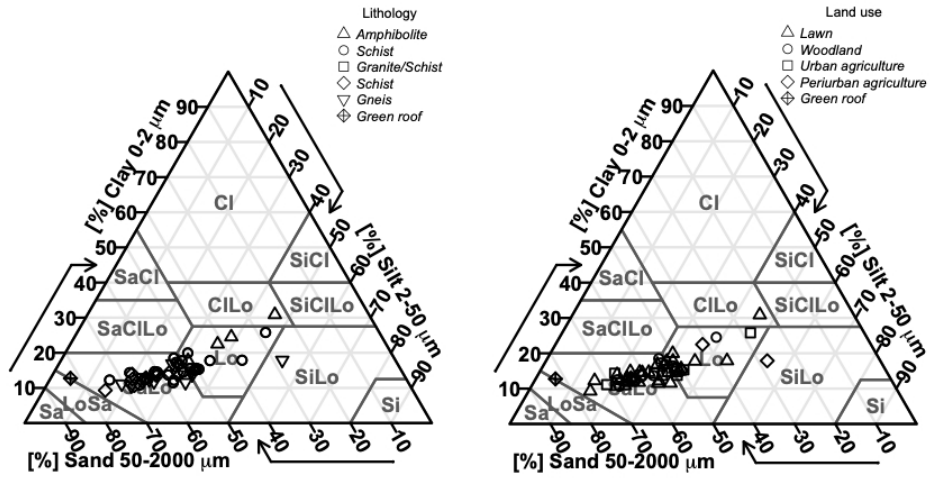


Figure 2. Soil texture as a function of land use and lithology. Plots were drawn using the soiltexture package for R (Moeys, 2014).

156x78mm (144 x 144 DPI)

1           **Composition and Chemical Properties of the Soils of the City of**  
2                           **Santiago de Compostela (NW Spain)**

3                           Remigio Paradelo\*, Cecilia Herbón, María Teresa Barral

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5  
6                           **SUPPLEMENTAL MATERIAL**

7  
8   Supplemental material contains two tables. Supplemental Table S1 shows the general  
9   characterization of each soil used in this study. Supplemental Table S2 shows the results  
10  of the Fe and Al extractions for each soil.

11

1 **Table S1. Main properties of the soils.**

Soil	Bulk density (Mg m <sup>-3</sup> )	Gravel (%)	Artifacts (g kg <sup>-1</sup> )	Clay (g 100 g <sup>-1</sup> )	Texture	EC	pH <sub>w</sub>	pH <sub>K</sub>	OC (g kg <sup>-1</sup> )	N (g kg <sup>-1</sup> )	C/N	Available P (mg kg <sup>-1</sup> )	----- (cmol <sub>c</sub> kg <sup>-1</sup> ) -----					
													CEC	Al ex	Ca ex	Mg ex	Na ex	K ex
1	0.87	6	0.4	31	Clay loam	164	5.6	4.4	40	2.9	14	14	20	0.3	3.2	0.9	0.2	0.4
2	0.91	16	1.8	25	Loam	89	5.9	4.5	34	2.5	13	8	16	0.3	3.4	1.1	0.2	0.7
3	1.18	25	1.9	18	Loam	54	5.4	4.4	23	1.9	12	40	10	0.7	1.4	0.4	0.1	0.3
4	1.01	29	4.0	15	Sandy loam	91	5.8	4.3	32	2.2	15	6	14	0.8	2.4	1.1	0.1	0.7
5	1.02	23	0.5	14	Sandy loam	152	5.9	4.8	49	3.2	15	25	17	0.1	5.5	1.1	0.2	0.6
6	0.71	14	0.6	20	Loam	78	5.6	4.7	70	5.4	13	4	18	0.7	0.9	0.4	0.2	0.2
7	0.89	38	1.0	16	Loam	138	5.5	4.1	40	3.3	12	68	17	1.2	1.6	0.5	0.2	0.5
8	0.88	31	23.7	11	Sandy loam	138	5.5	4.4	37	3.1	12	38	16	0.2	4.1	1.4	0.2	0.7
9	0.83	23	1.3	16	Loam	131	5.1	3.9	37	3.2	12	102	15	1.4	1.4	0.6	0.2	0.6
10	0.57	18	8.3	15	Sandy loam	182	5.9	4.7	37	3.2	12	72	19	0.1	6.4	1.3	0.3	0.7
11	1.16	26	1.6	18	Sandy loam	118	5.2	3.8	30	2.2	13	66	14	1.4	1.2	0.5	0.2	0.7
12	0.83	13	0.4	18	Loam	115	5.6	4.3	25	2.4	10	40	13	0.3	3.1	0.5	0.2	0.5
13	0.94	9	0.8	26	Loam	182	6.5	5.3	49	4.7	10	62	25	0.0	11.9	1.3	0.6	1.2
14	0.46	12	0.4	17	Sandy loam	104	4.9	3.8	69	4.6	15	5	27	3.5	0.3	0.3	0.5	0.6
15	0.85	30	1.2	12	Sandy loam	105	5.4	3.9	20	1.8	11	74	15	1.0	1.3	0.5	0.5	0.4
16	0.92	31	51.1	15	Loam	70	5.6	4.5	33	2.9	12	53	9	0.4	2.2	0.5	0.1	0.2
17	1.06	10	12.0	15	Loam	192	6.3	5.2	44	3.4	13	116	27	0.0	10.1	1.6	0.5	1.3
18	1.01	18	3.4	17	Sandy loam	147	5.9	4.8	43	3.5	12	81	22	0.1	5.9	0.9	0.5	0.7
19	1.09	25	3.5	12	Sandy loam	102	5.9	4.7	23	1.8	13	78	12	0.1	4.6	0.6	0.4	0.6
20	1.03	35	56.2	13	Sandy loam	283	6.5	5.7	63	4.1	16	79	27	0.2	20.1	1.3	0.3	0.9
21	0.93	24	7.1	11	Sandy loam	55	5.1	3.8	25	1.9	13	89	7	1.3	0.6	0.2	0.1	0.1
22	1.02	25	0.6	18	Loam	133	5.8	4.4	42	3.6	12	27	18	0.2	3.9	0.9	0.2	0.8
23	0.83	22	0.2	18	Loam	89	5.4	4.1	47	3.4	14	7	18	1.5	1.5	0.4	0.2	0.4
24	0.68	28	0.1	14	Sandy loam	139	4.7	3.8	35	2.6	13	21	15	2.5	0.3	0.2	0.2	0.3
25	0.54	13	1.1	16	Loam	123	4.8	3.6	110	6.0	18	10	36	4.1	1.3	1.1	0.2	0.7
26	0.83	30	12.9	15	Sandy loam	115	5.2	3.9	43	3.2	13	102	18	1.5	2.4	0.7	0.2	0.6
27	1.08	15	0.8	13	Sandy loam	83	5.9	4.3	18	1.4	13	8	10	0.4	2.7	1.0	0.1	0.5
28	0.94	27	4.9	11	Sandy loam	208	6.4	5.3	27	1.9	14	55	12	0.1	5.9	0.8	0.2	1.3
29	0.67	27	3.2	11	Sandy loam	160	5.3	4.0	34	2.7	13	80	15	1.1	2.5	0.6	0.2	0.6
30	0.73	23	1.9	12	Sandy loam	135	4.8	3.6	50	3.6	14	100	17	3.2	0.7	0.3	0.1	0.4
31	1.09	28	10.3	14	Sandy loam	217	6.9	6.1	26	2.0	13	101	16	0.2	11.3	1.0	0.1	1.0
32	0.88	11	5.6	17	Sandy loam	203	5.4	4.3	34	2.9	12	152	16	0.1	4.5	0.7	0.2	0.7
33	1.24	20	4.6	14	Sandy loam	122	5.7	4.5	24	1.9	13	115	15	0.1	5.0	0.8	0.1	0.7
34	1.25	22	42.5	15	Sandy loam	96	5.7	4.3	29	1.9	15	122	16	0.2	4.9	0.7	0.1	0.8
35	1.03	13	11.6	14	Loam	253	6.2	5.2	33	2.4	14	127	18	0.1	8.7	1.2	0.1	0.9
36	1.19	23	1.6	12	Sandy loam	69	6.3	5.2	16	1.5	11	81	6	0.1	3.1	0.4	0.1	0.3
37	0.89	13	2.3	12	Sandy loam	184	6.0	5.1	13	0.8	16	43	9	0.1	4.5	0.5	0.1	0.3
38	0.87	20	0.9	15	Loam	289	6.4	5.6	37	2.5	14	60	23	0.1	10.8	1.5	0.1	1.0
39	0.87	15	0.4	14	Sandy loam	73	5.0	4.2	24	1.4	17	3	12	1.7	0.0	0.1	0.1	0.3
40	1.06	23	3.7	12	Sandy loam	93	5.2	4.1	25	2.0	13	22	13	1.1	2.4	0.3	0.1	0.3
41	1.15	26	13.4	12	Sandy loam	83	5.8	4.6	28	1.7	16	35	18	0.2	4.4	0.6	0.1	0.8
42	1.11	24	2.0	13	Sandy loam	80	5.4	4.1	30	2.2	14	31	16	0.8	2.3	0.4	0.1	0.7
43	0.97	41	3.0	11	Sandy loam	174	5.0	4.0	45	3.4	13	20	17	0.5	4.0	0.7	0.1	0.8

44	0.85	28	1.4	15	Sandy loam	83	5.1	3.9	46	3.3	14	27	19	1.8	0.8	0.3	0.1	0.5
45	0.93	18	1.9	15	Sandy loam	99	5.8	4.4	37	2.8	13	12	19	0.4	3.4	0.6	0.1	0.6
46	1.15	21	1.7	13	Sandy loam	60	5.4	4.0	21	1.3	16	33	11	0.8	0.4	0.1	0.1	0.6
47	0.78	16	3.8	17	Sandy loam	93	5.7	4.2	31	2.0	15	108	16	0.6	3.8	0.6	0.1	0.8
48	0.94	27	15.4	13	Sandy loam	98	5.7	4.4	27	2.1	13	28	13	0.3	2.8	0.9	0.1	0.7
49	0.66	30	0.9	9	Sandy loam	169	5.7	4.4	30	2.4	13	43	13	0.3	2.6	0.7	0.1	0.8
50	1.11	13	6.5	12	Sandy loam	71	6.4	5.3	21	1.4	15	28	12	0.0	4.8	0.5	0.1	1.0
51	0.75	11	3.2	14	Sandy loam	115	5.6	4.3	30	2.4	13	27	15	0.3	3.0	0.6	0.1	0.9
52	0.34	30	1.0	13	Sandy loam	236	6.1	5.0	137	3.5	39	13	48	0.2	18.4	8.0	0.4	1.5
53	0.89	13	0.3	22	Loam	132	6.3	5.2	36	2.6	14	35	16	0.2	4.9	0.7	0.1	0.8
54	1.10	20	9.6	15	Loam	92	6.1	4.8	34	2.6	13	70	16	0.2	6.5	0.9	0.1	0.8
55	0.72	1	0.4	18	Silt loam	100	5.5	4.2	38	3.1	12	143	15	0.3	3.7	0.8	0.1	0.2
56	0.88	24	3.3	14	Sandy loam	120	5.7	4.5	41	3.2	13	14	18	0.2	4.9	0.6	0.1	0.7

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**Table S2. Selective extractions and related properties.**

Soil	pH <sub>Naf</sub>	P retention (%)	Fe <sub>DCB</sub> (g kg <sup>-1</sup> )	Fe <sub>ox</sub> (g kg <sup>-1</sup> )	Fe <sub>p</sub> (g kg <sup>-1</sup> )	Al <sub>ox</sub> (g kg <sup>-1</sup> )	Al <sub>p</sub> (g kg <sup>-1</sup> )	Al <sub>ox</sub> + 1/2Fe <sub>ox</sub> (%)
1	9.2	58	42	9.1	2.8	5.5	1.4	1.0
2	9.2	56	33	5.3	3.2	4.7	3.0	0.7
3	9.0	41	31	4.8	2.5	4.0	4.1	0.6
4	9.8	48	20	3.3	1.8	4.2	1.7	0.6
5	10.1	61	8	3.7	3.0	5.4	5.2	0.7
6	10.9	89	22	7.6	4.7	11.9	7.1	1.6
7	9.1	51	21	5.0	3.7	3.9	3.7	0.6
8	8.0	31	13	3.7	1.7	2.3	1.5	0.4
9	8.5	34	13	3.8	2.6	2.9	2.7	0.5
10	8.5	35	17	5.1	2.7	2.9	2.0	0.5
11	8.6	36	16	4.6	3.5	2.8	2.7	0.5
12	8.6	39	14	5.1	3.7	3.2	2.5	0.6
13	9.9	28	19	9.6	5.6	6.4	4.4	1.1
14	10.2	77	17	6.4	6.9	7.3	7.2	1.1
15	8.7	25	12	3.0	1.9	2.2	1.9	0.4
16	8.4	29	11	3.7	2.1	1.7	1.5	0.4
17	10.1	15	9	3.9	3.1	4.3	3.3	0.6
18	9.7	54	16	7.2	3.5	9.0	5.1	1.3
19	8.9	19	8	3.4	1.2	2.4	1.3	0.4
20	8.7	28	7	2.8	1.8	2.3	1.7	0.4
21	8.5	24	7	3.2	2.0	2.1	1.8	0.4
22	8.9	55	24	7.0	3.8	4.9	2.9	0.8
23	9.6	60	19	6.4	4.5	7.0	5.3	1.0
24	9.1	41	16	4.1	2.9	4.1	3.3	0.6
25	8.3	64	11	5.3	4.0	5.1	5.1	0.8
26	8.5	40	11	4.5	3.0	3.3	3.1	0.6
27	9.6	38	8	3.1	1.8	2.8	2.1	0.4
28	9.4	28	6	3.4	1.7	3.5	2.4	0.5

29	8.2	31	9	3.7	2.5	2.4	2.0	0.4
30	8.3	41	8	3.5	2.6	3.5	3.2	0.5
31	9.2	26	8	3.3	1.3	2.6	1.6	0.4
32	9.2	31	10	4.7	3.3	3.9	2.8	0.6
33	9.1	22	10	4.1	2.1	3.2	2.5	0.5
34	8.6	27	10	3.9	2.3	2.8	2.1	0.5
35	9.0	29	10	4.6	2.5	3.4	2.3	0.6
36	8.9	22	11	3.3	2.0	3.0	2.5	0.5
37	9.0	18	11	3.5	1.5	1.8	0.9	0.3
38	8.8	28	14	2.8	1.5	1.3	1.1	0.3
39	10.6	57	10	2.9	2.5	4.8	3.8	0.6
40	9.1	31	9	3.3	1.8	3.1	2.1	0.5
41	9.0	26	8	2.1	1.1	2.2	1.5	0.3
42	9.3	37	11	4.1	2.6	3.6	3.1	0.6
43	7.8	27	9	1.6	0.9	1.6	1.3	0.2
44	9.6	48	11	4.2	2.8	5.0	4.6	0.7
45	10.8	64	13	4.3	2.3	6.3	3.9	0.8
46	10.5	37	9	3.2	1.9	3.5	3.4	0.5
47	8.8	34	12	4.6	2.9	3.2	2.6	0.6
48	9.1	32	8	2.9	1.6	3.0	2.2	0.4
49	9.3	38	6	2.9	1.9	3.1	2.4	0.5
50	9.7	32	8	3.8	2.0	3.4	2.3	0.5
51	10.3	22	10	3.7	3.0	4.0	3.3	0.6
52	7.5	19	2	2.1	0.7	1.0	0.6	0.2
53	8.7	43	45	4.7	1.9	4.7	3.2	0.7
54	9.9	19	15	6.1	3.8	4.5	3.4	0.8
55	9.5	22	15	6.9	6.0	4.5	3.7	0.8
56	9.1	17	12	2.2	2.1	2.0	2.0	0.3

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