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1 Pedological characteristics of artificialized soils: a snapshot

2

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12

13 **Abstract**

14

15 The onset of industrialization entailed the increase in soil artificialization worldwide.

16 Soils from artificialized zones (SAZ) are the result of urban, industrial, traffic, mining or

17 recreational land use. Knowledge of their characteristics is a prerequisite for evaluating

18 the ability of SAZ to perform key functions and provide soil ecosystem services. Based

19 on a selection of 102 papers published between 1991 and 2017, this article aims at

20 providing a quantitative vision of the pedological characteristics of the different

21 categories of SAZs as a function of the land use and soil type (natural profile, soil

22 developed on allochthonous material). We show that, overall, the inherent

23 characteristics of SAZ topsoil generally depend on the soil type - soil of allochthonous

24 material being more stony and poorer in the < 2 µm fraction - while manageable

25 characteristics are a function of both the soil type and the land use, with the exception of

26 pH that is mainly driven by the land use. However, a good characterization of SAZs

27 requires a more systematic description, sampling and analysis to obtain comprehensive

28 knowledge of their characteristics as several features are still too rarely measured such

29 as cationic exchange capacity, electrical conductivity, soil depth, and nutrient
30 concentrations. Sealed soils are still too rarely considered despite their large surface
31 area. Such a characterization would allow a better management of the ecosystem
32 services that SAZs fulfill.

33

34 **Keywords:** urban soils, mining soils, industrial soils, recreational soils, traffic soils,
35 artificialization, land use, soil properties, anthropogenic impact

36

37

38 Introduction

39

40 As Vitousek et al. (1997) highlighted several years ago, man has profoundly modified
41 terrestrial ecosystems, including the soil compartment. This change is particularly
42 extreme in the case of artificialized environments. In these environments, the question
43 arises of the persistence of the soil functions as defined by e.g. Robinson et al., (2009)
44 and Dominati et al. (2010). These functions depend on the soil characteristics. Some of
45 them, considered as inherent, are therefore little impacted by human activities that
46 initially focused on agriculture (Karlen et al., (1997); Robinson et al., (2009); Dominati et
47 al., (2010)). However, for artificialized soils such as Technosols for example, the
48 hypothesis of no human impact on the so-called inherent characteristics is no longer
49 valid (Barles et al., 1999). More generally, the actual effect of artificialization on the
50 pedological profile and associated soil characteristics is still insufficiently documented,
51 with in particular the absence of synthesis except for organic matter, nutrients or
52 contamination (e.g. Joimel, 2016). It is essential, however, to determine the soil
53 characteristics in order to assess the functions they provide, such as 1) water flow and

54 retention, 2) retention and cycling of nutrients, 3) physical stability and support, 4)
55 maintenance of biodiversity and habitat, and 5) preservation of the natural soil heritage
56 (Commission of the European Communities, 2006; Bone et al., 2010). Knowledge of both
57 their inherent and manageable (Dominati et al., 2010) characteristics is therefore a
58 prerequisite for evaluating the ability of soils in artificialized areas (SAZ) to provide
59 services in order to propose appropriate management.

60

61 Artificialized areas are generally identified according to their land-use as defined by the
62 European Corine Land Cover inventory (CLC) that differentiates (i) urban fabric; (ii)
63 industrial, commercial and transport units; (iii) mine, landfill; and (iv) artificial non-
64 agricultural. The soils of these artificialized zones were categorized by the International
65 Union of Soil Sciences (IUSS) in 1998 with land use as the determining factor (the
66 SUITMA categorization for Soils of Urban, Industrial, Traffic, Mining and Military Areas).

67 It is postulated that a given land use implies a certain degree of soil artificialization
68 understood as degradation as shown by Vasenev et al. (2012) who point out the
69 "increasing human load" when moving from recreational areas to residential and
70 industrial areas. It is also implicitly postulated that the more "artificialized" the soils are,
71 the more degraded they are (Kurucu and Chiristina, 2008; Vasenev et al., 2012; Peng et
72 al. 2013; Morel et al., 2015) and that they will be unable to perform their functions,
73 leading eventually to the abandonment of artificial soils considered as sterile.

74 Attempts at characterizing the impact of artificialization by comparing SAZ
75 characteristics with those of soils under natural vegetation or agriculture are rare,
76 except within the study by Joimel et al. (2016) for French SUITMAs. They showed that
77 SUITMAs exhibit a greater variability of characteristics than that recorded for forested
78 or agricultural soils. The reasons for this variability may lie in that:

- 79 1- all the SUITMAs were grouped together while specificities might occur among the
80 different land uses;
- 81 2- each SUITMA category contains soils with contrasted levels of artificialization
82 and thus different pedological profiles, ranging from (pseudo)natural soils to
83 Technosols (Morel et al., 2005; Rossiter, 2007; IUSS Working Group World
84 Reference Base, 2015).

85 This paper aims at (i) providing a quantitative vision of the pedological characteristics of
86 the different categories of soils of artificialized zones (SAZ) in relation to a soil profile
87 categorization that we developed based on the descriptions available in the literature
88 (called soil types hereafter), and in comparison to those of other environments (natural
89 vegetation and cultivated soils), and (ii) identifying some of the drivers of their
90 variability (land use or soil type). The level of contamination is beyond the scope of this
91 paper.

92

93 2. Methodology

94

95 2.1. Building the corpus of scientific papers

96

97 In France, in 2017, a pluridisciplinary and collective scientific state-of-the-art on the drivers
98 and the environmental, social and economic effects – positive and adverse- of soil
99 artificialisation was published (Béchet et al., 2017). Among a global corpus of about 2500
100 scientific references a corpus of 970 articles on SUITMAs was constituted from an
101 automatic query on the Web of Science (WoS) on the basis of the script presented in SI-
102 1. From this corpus, only papers dealing with pedological characteristics were kept for

103 the present review. It was further enriched with additional research on the WoS
104 including the following key words: urban or mining or industrial and soil and pH or
105 cation exchange capacity (CEC) or electrical conductivity (EC) or gravel or stone (coarse
106 elements) or carbonates, or organic matter or compost or C cycles. Articles focusing on
107 agricultural soils and agricultural activities were excluded as agriculture was not
108 considered as artificialized soils. Only book chapters and papers in referenced journals
109 were selected.

110 Out of this corpus a database was built with all the studies that fulfilled the following
111 two conditions:

112 (i) the soils studied could be assigned with the provided information to a given land
113 use;

114 (ii) the article contained pedological information and data for surface soil horizons (0
115 to 0.3 m maximum) and/or a deep horizon (> 0.4 m).

116 The resulting database contains data gathered from 102 articles published from 1991 to
117 2017.

118 In the database, the soils of the considered studies were assigned to a land use category.
119 Following the CLC classification, we classified the artificialized surfaces into urban,
120 industrial, mining, traffic and recreational, the latter referring to parks and urban
121 forests. Since private gardens were referred to as “residential” in most papers, they were
122 included in the “urban” land-use. The urban class may also include soils from industrial,
123 recreational or traffic areas when no further information was provided than “*soils*
124 *sampled in the city of...*”, resulting in a relatively heterogeneous category. In addition, in
125 order to provide a vision of the pedological characteristics of the SAZs with reference to
126 soils in other environments (forest, cultivated land...), “control” or “natural” soils, which
127 were explicitly designated as such in the articles, were also entered in the database.

128 They were categorized as soils with “natural vegetation”, “crop cover” or “unspecified
129 cover”.

130 The soils entered in the database consisted either of a single soil profile or a topsoil
131 sample; the latter consisted either of a single sample or of the average value of a set of
132 samples (counted as one, as few authors gave individual data). Based on the information
133 at hand, and when a minimal description of soil profiles was provided, we were able to
134 categorize the corresponding soil profiles into four rough classes, namely “natural soil
135 profile”, “natural truncated soil profile”, “soil profile developed on allochthonous
136 materials (of natural or technogenic origin)”, and “sealed profile”. When the description
137 was reduced to “mining soil or urban soils” without any further specification, the soil
138 was categorized in a fifth class called unspecified unsealed soil profile.

139 Both manageable and inherent characteristics were entered in the database. Manageable
140 characteristics are soil water pH, soil organic carbon (SOC) content, cation exchange
141 capacity (CEC), electrical conductivity (EC) and bulk density. Nutrient concentrations
142 were either too seldom reported or were measured with methods that were too
143 different to be compared. Thus, N, P and K were not included in the database. The
144 inherent characteristics recorded were stoniness (coarse element content) and < 2 μm
145 fraction content. For each study, we also recorded the morphology of the soil profiles (i.e
146 description of profile), the type of soil used as a reference, as well as the occurrence and
147 nature of artefacts (here defined as by-products derived from industrial or artisanal
148 activities).

149 Methods used to measure the different parameters varied for the different studies. Only
150 data obtained with methods considered as comparable were entered in the database.
151 Nevertheless, a variability due to the various methods used cannot be excluded, that is
152 the reason why the parameters were presented as classes (see below). Soil water pH

153 was measured with the soil/water ratio varying from 1/1 (Chichester and Hauser, 1991;
154 Johnson and Skousen 1995; Hearing et al., 2004; Howard et al., 2013) to 1/5 (Nikiforova
155 et al. 2014); soil organic carbon (SOC) content was measured by wet (e.g. Jim, 1998a) or
156 dry (e.g. Abel et al., 2015a) combustion, CNS analyser (e.g. Hiller 2000; Norra et al.,
157 2008), dichromate oxidation (e.g. Wang et al., 2007; Oliveira et al., 2014; Ahirval and
158 Maiti, 2016; Pellegrini et al., 2016); cation exchange capacity (CEC) was measured after
159 ammonium acetate extraction (e.g. Johnson and Skousen, 1995; Jim, 1998a; Fu et al.,
160 2011; Ahirval and Maiti, 2016; Pellegrini et al., 2016) or cobalt hexamine extraction (e.g.
161 Capilla et al., 2006), electrical conductivity (EC) was measured with the soil/water ratio
162 varying from 1/2 (Johnson and Skousen, 1995) to 1/2.5 (Greinert, 2015); bulk density
163 was measured on clods (Jim, 1998a) or by the cylinder methods (e.g. Oliveira et al.,
164 2014; Ahirval and Maiti, 2016); particle size fractionation was performed by sieving and
165 Stocks law (e.g. Jim, 1998a; Schleuß et al., 1998; Hiller, 2000; Oliveira et al., 2014;
166 Greinert, 2015) or sieving and the pipette method (e.g. Capilla et al., 2006; Ahirval and
167 Maiti, 2016; Pellegrini et al., 2016). Coarse elements, when measured, were generally
168 defined as > 2 mm without specification of an upper boundary size limit (e. g. Hiller,
169 2000; Beyer et al., 2001; Golubiewski et al., 2006). Schleuß et al. (1998) defined them as
170 gravels and stones that were less than 0.20 m in size according to the IUSS Working
171 Group WRB (2015). Jim (1998a) also mentioned boulders.

172

173 2.2. Database structure

174

175 For each parameter considered, the data were organized into classes. Consequently, the
176 database does not contain the absolute value of each soil parameter considered for each

177 soil, but the number of soil samples belonging to each class of the parameter considered.
178 The classes were defined according to international references as specified for each
179 parameter in the figure captions (www.fao.org; FAO, 1993; Jim, 1998a, b; Baize, 2000;
180 Schoeneberger et al., 2002; Vrščaj et al., 2008, among others...).

181 Two depths were considered: topsoils and subsoils. Topsoil thickness was usually 0.3 m,
182 but ranged in some cases from 0.05, 0.10, 0.15, 0.20 to 0.30 m or was sometimes not
183 even specified (Lottermoser et al., 1999; Flynn et al., 2003; Chung et al., 2005; Wahsha et
184 al., 2016). This may have induced a bias, notably for SOC. When several layers were
185 analyzed within the 0.3 m, a mean value was calculated. The so-called subsoil layer
186 consisted in the soil horizon ideally below 0.4 m, but the limit could be between 0.4 and
187 0.6 m. When soil sampling was more superficial than 0.4 m, no subsoil was recorded.

188

189 2.3. Data representation and statistical treatments

190 Tables 1 and 2 present the number of topsoil and subsoil samples respectively for each
191 soil category within each SAZ type and for each parameter. In addition, Table SI-2 gives,
192 for each of the papers included in the database, the type of land use, the existence of a
193 reference soil (where relevant), the type of sample (surface or profile), and the
194 pedological characteristics measured. Data were further represented in Figures SI-1
195 and 2 as radar plots for references and SAZs topsoils and subsoils with more than eight
196 occurrences. Correspondence analysis (CA) was performed for each parameter and for
197 the soil types, SAZs and references with more than eight occurrences. In order to
198 identify the similarity among the different soil types/SAZs and references, an
199 agglomerative hierarchical cluster analysis (AHC) was performed on the two first factors
200 of the CA.

201

202 3. Results and discussion

203 3.1 Location and publication date of the articles contained in the database

204

205 The earliest papers contained in our database were published in the early 90s and
206 reported studies related to mining soils, following the decommissioning of many mines
207 (Figure 1). Among the articles collected, studies dealing with soils associated to traffic,
208 urban and recreational areas only appeared from the mid-90s. Lastly, soils associated to
209 industry appeared after 2000. The total number of studies related to mining,
210 recreational and urban soils in the database is about the same, around 35 to 40, while
211 those focusing on traffic and industrial soils are less numerous with only 15 and 10
212 studies respectively (Figure 1).

213 Studies were mainly performed for European sites (accounting for 45 to 65 %
214 depending on the land use considered, Figure 2). Studies in North America (mainly the
215 USA) and East-Asia are also well represented in the database (5 to 40 %), while we
216 found only few studies for the rest of the world, except for mine soils. Lastly, only a third
217 of the studies provided a reference soil. For the latter, the land use was described only in
218 60 % of the cases, most of it being covered by natural vegetation (Figure 3).

219

220 3.2. Morphological characteristics of soils of artificialized zones

221

222 **SAZ profiles are generally poorly described.** When described, the profiles are not
223 classified according to any pedological classification. Only a few studies identify them as
224 Anthrosols or Technosols according to the WRB (IUSS Working Group WRB, 2015). For
225 one third of the urban soils, and 70 % of the industrial soils, no description at all was
226 provided, with the notable exception of soils in mining areas. Indeed, for mining soil, the

227 use of the soil as “dump” or “tailing” allowed an easy categorization as soil profile
228 developed on allochthonous materials, resulting in a particularly low proportion of
229 unspecified profiles (10 %, Figure 4).

230 **Soils developed on allochthonous materials of natural or technogenic origin are**
231 **the most common SAZ profiles specified.** They represent more than 50 % of cases in
232 urban and mining contexts and 10 % to 40 % of cases for the other SAZs (Figures 4 and
233 5). However, for these soils, the substrate was rarely explicitly described, despite its
234 potential diversity and its importance in soil profile development. Natural soil profiles
235 represented a maximum of 20 % of all the studied profiles and were mainly encountered
236 in recreational, industrial and urban contexts. When encountered in a mining context
237 (less than 10 % of the cases), they consisted of soils "not physically disturbed" but
238 considered as receivers of airborne particles from mining or associated smelters or
239 impacted by acid mine drainage. Truncated natural soil profiles were only encountered
240 in mining contexts and sealed soils in traffic areas, as expected. Both were nevertheless
241 poorly represented in the database (13 and 5 cases respectively): truncated natural soil
242 profiles were thus merged with natural soil profiles in the rest of this analysis and sealed
243 soils were not further considered.

244 **The vertical differentiation of the SAZs is strongly dependent on the nature of the**
245 **soil profile.** While the soils with a natural or pseudo-natural pedon (possibly truncated
246 at the surface) comprise horizon types and sequences that depended on the nature of
247 the native soils present in the area, the soils developed on allochthonous materials are
248 characterized by clear limits between layers generally strongly marked by their
249 formation history (e.g. Jim, 1998a; Abel et al., 2015a, Figures 5a, b, e, f, g). The nature of
250 the parent materials is generally markedly different from native materials with a strong
251 vertical contrast with depth (Figures 5c, e). Pedogenetic development is often quite

252 limited with an A over C profile-type (Murolo et al., 2005, Figures 5d, f) as these soils are
253 rather young as compared to natural soils.

254 Lastly, **SAZs are often characterized by a complex pattern of spatial variability**
255 resulting from the superimposition of the complexity of their recent history on the
256 natural heterogeneity. In some cases, the spatial variability becomes metric to
257 centimetric with discontinuities in the soil cover as in the extreme case of soil
258 development in pavement joints (Burghardt and von Bertrab, 2016, Figure 5h).

259

260 3.3. Inherent pedological characteristics of soils of artificialized zones

261

262 Inherent soil characteristics are considered as stable over a time scale of a few years
263 (Dominati et al., 2010) in contrast to manageable soil characteristics, which are
264 considered as more dynamic. The inherent soil characteristics encompass mainly
265 texture, depth, structure at depth, horizonation and the nature of the mineral phases
266 (Dominati et al., 2010).

267

268 *3.3.1. SAZ stoniness and fine (< 2 µm) fraction content is a function of land use and soil type*

269 Stoniness is usually considered when assessing agronomic performances because the
270 presence of coarse materials modulates the surface available for water infiltration,
271 water storage and root development (Yilmaz et al., 2018). The non-consideration of
272 these coarse elements may result in an overestimation of the C and N stocks (Rytter,
273 2012). Stoniness may also create fissures at the interface with fine backfill materials
274 (Cousin et al., 2003; Wang et al., 2018), thus allowing for preferential flows. However,
275 the abundance of coarse elements was recorded in only nine percent of the articles,
276 mainly from soils developed in allochthonous materials (Tables 1 and 2), resulting in 58
277 and 42 surface and deep horizons respectively (including reference soils, Tables 1 and
278 2). This low amount of data on soil stoniness is not surprising since Bünemann et al.
279 (2018) concluded in their literature review that stoniness was not considered as an
280 important soil characteristic to define soil quality. The two first factors of the CA
281 performed for the topsoils and subsoils explain 95 and 96 % of the total variance
282 respectively (Figures 6a and 7a). In both case, three poles are identified by the AHC
283 made on the two CA factors, one very rich in coarse elements, one with less than 1 %

284 coarse element and one with 1 to 25 % of coarse elements (Figures 6a and 7a).
285 Nevertheless, these results showed that the reference soils in the database contained
286 less than 25 % of coarse elements (whatever the land use considered, agriculture or
287 natural vegetation, Figure 6a), which is consistent with results of the LUCAS European
288 soil database showing that only Mediterranean and mountain soils had higher coarse
289 element contents (European Commission – JRC - ESDAC, 2020). When considering SAZs,
290 the amount of coarse elements is higher than in natural soils, especially at depth
291 (Figures 7a). This global trend masks a more complex reality. Artificialized natural soil
292 profiles were poorly represented and did not differ from the reference soils in terms of
293 stoniness. Most of the soils developed on allochthonous materials in urban and
294 recreational zones contained 5 to 25 % of coarse elements as seen for the reference
295 soils, with a small proportion (10 %) containing more than 25%, while mining soils on
296 allochthonous materials contained generally between 50 and 80 %, of coarse elements
297 in the topsoils (Figure 6a). Industrial soils exhibit a more complex distribution pattern
298 and traffic soils on allochthonous materials have a low amounts of coarse elements in
299 the topsoils (Figure 6a). At depth, all SAZs contained more coarse elements than the
300 reference soils, mining soils remaining the ones with the largest amounts of stones and
301 gravels (Figures 7a). Indeed, a layer of “arable” soil is often applied to the surface
302 notably in recreational soil profiles developed on allochthonous material (e. g. Jim,
303 1998a; Abel et al., 2015a).

304

305 Conversely, the content of the $< 2 \mu\text{m}$ fraction was considered since it controls most of
306 the soil parameters such as cation exchange capacity (CEC), structural stability, and
307 water holding capacity. The results were measured in fine earth ($< 2 \text{ mm}$). The
308 distribution of the reference soils in the different classes of $< 2 \mu\text{m}$ percentage is similar

309 to that provided at the global scale by Shangguan et al. (2014) and Dai et al. (2019). The
310 two first factors of the CA performed for the topsoils and subsoils explain 98 and 93 % of
311 the total variance respectively (Figures 6b and 7b). In both cases, three poles are
312 identified by the AHC made on the two first CA factors, one with concentrations in the <
313 2 μm fraction lower than 15 %, one with a contribution of soils having concentrations in
314 the < 2 μm fraction higher than 35 % and, one with a large contribution of soils having a
315 < 2 μm fraction ranging from 15 to 35 % (Figures 6b and 7b). In general, SAZ topsoils
316 have a < 2 μm fraction lower than 15 % (Figure 6b), unlike reference topsoils, which
317 have a < 2 μm fraction content between 35 and 60 %. However, topsoils of urban natural
318 soil profiles, mining soils on allochthonous materials and unspecified recreational soils
319 may exhibit concentrations in the < 2 μm fraction ranging from 15 to 35 % as some
320 topsoils of the reference soils (Figure 6b). At depth, the situation is more contrasted
321 with natural profiles that are clearly differentiated from SAZs. Recreational soils on
322 allochthonous materials have the lowest concentration in the < 2 μm fraction (Figure
323 7b). Since the same SAZs are also richer in coarse elements than the reference soils, the
324 < 2 μm fraction in the whole soil matrix is even lower compared to the reference soils.

325

326 This analysis clearly shows that, while as expected SAZ with a natural profile do not
327 differ much in terms of stoniness and < 2 μm content from reference soils, SAZ on
328 allochthonous materials are generally stonier with a lower < 2 μm fraction.

329

330 *3.3.2. SAZs are characterized by the presence of artefacts*

331 Beside the occurrence of the minerals classically encountered in soils, a characteristic of
332 SAZs is their content in artefacts of different sizes, from coarse elements, which
333 constitute a large fraction of the allochthonous soil profiles, to micro artefacts such as

334 ash deposition also encountered in SAZs with natural profiles (Fu et al., 2011; Howard
335 and Olriki, 2016).

336 The nature of these materials depends on the type of artificialized zone. Due to their
337 generally long and complex history, urban soils on allochthonous material contain a
338 wide variety of technogenic materials such as building/demolition materials (brick
339 (Nehls et al., 2013), mortar, nails, glass, wood, plaster (Schleuß et al., 1998; Howard et
340 al., 2013; Greinert, 2015)), ashes, coals, slags, asphalt and ferrous residues (Howard et
341 al., 2013), industrial deposits (Greinert, 2015), municipal waste (Schleuß et al., 1998;
342 Greinert, 2015), and stormwater sediments (El-Mufleh et al., 2014a,b). On the contrary,
343 other SAZ contain more specific materials related to their land use: (i) disturbed
344 recreational soils may contain demolition materials (Abel et al., 2015a) or filling with
345 materials of natural origin (Jim, 1998a); (ii) soils from traffic areas contain building
346 materials, ashes, coals, slag, ballast (Hiller, 2000), natural embankment (Kida and
347 Kawahigashi, 2015) or dredged sediments for soils near waterways (Capilla et al., 2006);
348 (iii) soils from quarries contain rock debris with a large particle size distribution (Fu et
349 al., 2011), while metalliferous mining soils contain sludge, mine wastes (Pellegrini et al.,
350 2016) or even foundry wastes when associated with smelters, and soils from coal and
351 lignite mining contain various types of spoils (Shankar et al., 1993; Kundu and Ghose ,
352 1994; Pedrol et al., 2010; Adeli et al., 2013; Clouard et al., 2014; Ahirwal and Maiti, 2016;
353 Kolodziej et al., 2016), with the presence of fossil carbon. To a much less extent, airborne
354 technogenic materials of the same nature are also encountered in SAZ with natural
355 profiles (Fu et al., 2011; Howard and Olriki, 2016).

356

357 For all the inherent characteristics, the main differences are observed between the
358 reference soils and soils on allochthonous materials. The latter are modified to such an

359 extent that the distinction between inherent and manageable properties might not be
360 meaningful anymore. In addition, it remains to be clarified whether allochthonous
361 materials will follow the same line of evolution as natural parental material.

362

363 3.4. Soil manageable pedological characteristics in soils from artificialized zones

364

365 Soil characteristics are considered as dynamic or manageable (Dominati et al., 2010)
366 when they can be impacted by land use or management decisions (Karlen et al., 2003).
367 In the following, we address the physical manageable properties (bulk density,
368 hydrodynamic properties, aggregation), organic matter concentration and physico-
369 chemical manageable characteristics (pH, CEC, electrical conductivity).

370

371 *3.4.1. SAZs have a large range of bulk densities depending on their land use and* 372 *soil profile type*

373

374 The two first factors of the CA performed for the topsoils and subsoils explain 79 and 75
375 % of the total variance respectively (Figures 6c and 7c).

376 The topsoil bulk densities of reference soils are lower than 1.4 g cm^{-3} under natural
377 vegetation with a mode at $1\text{-}1.2 \text{ g cm}^{-3}$ (Figure 6c). Cultivated soils have a bulk density
378 mode at $1.4\text{-}1.55 \text{ g cm}^{-3}$ with nearly 10 % of the soil having a bulk density greater than
379 1.55 g cm^{-3} (Figure 6c), which agrees with results reported by Kern (1995). SAZs have an
380 even bulk density distribution from low densities ($< 1 \text{ g cm}^{-3}$) to densities of 1.7 g cm^{-3} ,
381 with a small percentage of very high bulk densities ($> 1.8 \text{ g cm}^{-3}$, Figure 6c). This
382 distribution indicates a higher variability linked both to the land use and the soil profile
383 type. Recreational soils with natural profiles exhibit bulk densities comparable to those
384 measured for reference soils, while natural soils at mining sites have a higher proportion

385 of bulk densities larger than 1.55 g cm^{-3} (35 %) since their topsoil has often been
386 stripped (truncated) and compacted (Figure 6c). SAZs on allochthonous materials
387 exhibit bulk densities comparable to those encountered in cultivated soils (Figure 6c).
388 Edmondson et al. (2011) and Pouyat et al. (2007) showed that the urban soils for the
389 City of Leicester (UK) (136 sites with a median bulk density class of $0.81\text{-}1 \text{ g cm}^{-3}$) and
390 Baltimore (USA) (0.71 to 1.74 g cm^{-3} , with a median value of 1.18 g cm^{-3}) were less
391 compact than those of the surrounding agricultural area, while Jim's study of the city of
392 Hong Kong (1998b) showed that in two-thirds of the cases, urban soils of alignment
393 trees were often very compacted (1.4 to 2.2 g cm^{-3}), with bulk densities greater than 1.6
394 g cm^{-3} , which is the threshold for root development (Hanks and Lewandowski, 2003).
395 Scharenbroch et al. (2005) also showed that the bulk density was a function of the age of
396 the residential area with bulk densities around 1.73 g cm^{-3} in new residential areas
397 against 1.41 g cm^{-3} in old residential areas. In recreational areas, studies showed an
398 extreme spatial variability of the topsoil bulk density with locally very high bulk density
399 values linked to the spatial variability of trampling (Jim, 1998a; Cakir et al., 2010).
400 Traffic topsoils on allochthonous materials have very low bulk density (Figure 6c). At
401 depth, SAZs generally exhibit higher bulk density than reference soils, especially mine
402 soils developed on allochthonous materials (Figure 7c). This is however not the case for
403 urban soils on allochthonous materials or recreational soils (Figure 7c).
404 The strong compaction of certain types of SAZ results in (i) a reduced total porosity, (ii)
405 a few coarse pores and a large percentage of fine pores (Baumgartl, 1998; Yang and
406 Zhang, 2011), which induces (iii) low aeration, (iv) a poorly effective drainage (Jim,
407 1998b) and increases (v) the risks of runoff and erosion (Gregory et al., 2006).
408

409 *3.4.2. SAZs have a highly variable organic carbon content*

410

411 Soil organic carbon (SOC) content is one of the most frequently reported soil parameters
412 in the database with 63 references resulting in 410 topsoil and 100 subsoil SAZ SOC data
413 respectively (Tables 1 and 2). In France, a country considered as having a very high
414 pedovariability (Minasny et al., 2010), Joimel et al. (2016) observed that the median soil
415 organic carbon (SOC) concentration of the topsoil (0-0.3 m) was 9 g kg⁻¹ for vineyards
416 and orchards, 14.9 g kg⁻¹ for cultivated soils, 24.8 g kg⁻¹ for grassland, 26.2 g kg⁻¹ for
417 gardens, 26.8 g kg⁻¹ for forests and 37.3 g kg⁻¹ for SAZs grouped in one category (all
418 SUITMAs). The latter seem thus to contain higher SOC concentrations than vineyards
419 and orchards, agricultural and grassland soils, while the difference is less marked with
420 forest soils. On the other hand, the authors showed that the variability of the SOC
421 concentrations in SAZs was higher than that observed for other land uses (as also seen
422 on Figure 6d). This result probably derives from the high variability of the soil types
423 grouped under the term "SAZ" as observed in our database.

424 The two first factors of the CA performed for the topsoils and subsoils explain 74 and
425 64 % of the total variance respectively. The AHC made on the two first CA factors
426 identified three types of profiles for the topsoils and four at depth (Figures 6d and 7d).

427 While urban and industrial topsoils have a comparable level of SOC to natural soils
428 whatever the soil profile considered, 40% of traffic and 50% of mining topsoils on
429 allochthonous materials are very poor in SOC (Figure 6d). Recreational natural profiles
430 also exhibit a large amount of very poor SOC topsoils, notably in natural profiles (Figure
431 6d). Soil organic carbon concentrations in the top 0.30 m of urban zones are often higher
432 than in agricultural soils (Pouyat et al., 2006; Lorenz and Lal 2009; Edmondson et al.,
433 2014; Vasenev et al., 2014; Cambou et al., 2018; Figures 6d) and sometimes higher than

434 those of some forest soils, in the case of soils in residential neighbourhoods (Pouyat et
435 al., 2002; Cambou et al., 2018). It may be one of the factors responsible for the lower
436 bulk density measured in urban topsoils (Edmondson et al., 2011; 2014). In addition,
437 SOC concentrations in urban soils vary widely. For example, in the city of Stuttgart,
438 Germany, SOC concentrations in soils ranged from 5 to 207 g C kg⁻¹ (Lorenz et al., 2006).
439 The soil cover for a given land use may be responsible for this variability. As an example,
440 tree-planted gardens had higher SOC concentrations than non-planted community
441 gardens or non-domestic spaces planted with trees or lawns (Edmondson et al., 2014).
442 However, the difficulty of this analysis lies in the very variable depth of sampling of the
443 topsoil horizons, which ranges from 0.05 to 0.30 m depending on the authors. This
444 variability probably induces a bias as SOC decreases exponentially with depth over the
445 first 0.50 m of soil.

446 At depth, the differences are more marked among SAZs, especially soils on
447 allochthonous materials, with some mining soils having lower concentrations than both
448 the reference soils and urban soils (Figure 7d). Conversely, some urban and industrial
449 soils have a higher SOC concentration at depth than the reference soils (Figures 7d) as
450 also shown by Cambou et al. (2018) for Paris and New York. In some remediated soils in
451 New York City, for instance, the concentrations reached 160 g C kg⁻¹ at 0.40 m depth and
452 were still 80 g C kg⁻¹ at 1 m depth (Huot et al., 2017). Soil organic carbon concentration
453 along the whole soil profile is also investigated to assess the soil potential for climate
454 change mitigation through the calculation of carbon stocks. The depth of SOC
455 accumulation seems to be related to the history of use, which determines the dynamic of
456 the SOC stock changes (Bae and Ryu, 2015; Cambou et al., 2018) but is still too seldom
457 measured to give reliable trends (Cambou et al., 2018).

458 However, some authors have shown that urbanization, through land-use change and the

459 removal of vegetation cover, creates in some areas a critical SOC stock reduction, e. g. a
460 30 % reduction in 25 years for an exponentially growing city such as Changzhou
461 (increase in surface area by a factor of 10 in 20 years from 1980 to 2000; Tao et al.,
462 2015). Obviously, organic carbon stock decreases or increases in SAZs need to be
463 investigated in greater detail.

464

465 *3.4.3. The pH of SAZs is mainly basic*

466 The water pH is the other most frequently reported soil parameter in the database with
467 64 references resulting in 416 topsoil and 115 subsoil SAZ pH data (Tables 1 and 2).

468 The two first factors of the CA performed for the surface and deep horizons explain 70
469 and 66 % of the total variance respectively. The AHC made on the two first CA factors
470 identified three types of profile for the topsoils and four at depth (Figures 6e and 7e).

471 pH of all SAZs is higher than that of the reference soils (Figures 6e and 7e). This is in
472 agreement with Joimel et al. (2016) who found that the pH of SAZs was mainly basic
473 while the pH of agricultural and natural soils varied over a very wide range with rather
474 acidic soils in forest and grassland, neutral in agriculture and rather basic for orchards
475 and vines.

476 pH values above 7 observed for urban, recreational, industrial and traffic infrastructure
477 at both depths (Figures 6e and 7e) are due to the frequent presence of 1) technogenic
478 carbonated materials, notably due to rubble for profiles on allochthonous materials (Jim,
479 1998b; Abel et al., 2015b); 2) carbonate, siliceous and fossil carbon microparticles for all
480 profile types (Howard and Orlicki, 2015), whose pH ranges mostly from 8 to 12; 3)
481 and/or the use of road deicing products in winter, which may result in the formation of
482 salty alkaline soils as observed in a cold urban context (Nikiforova et al., 2014).

483 Mining soils and sometimes industrial soils can exhibit very acid pH values (Figures 6e

484 and 7e), with low pH (< 5) accounting for 40 to 50% of the cases depending on the soil
485 type considered. In the case of soils from mining areas, the acidic pH are usually
486 restricted to the metalliferous areas, since soils from coal and lignite mine areas are
487 predominantly neutral to alkaline (Ogala et al., 2012). Some very low pH (less than 4.5)
488 are observed in nearly 30 % of the allochthonous soils from metalliferous areas (Figure
489 7e) that can notably be due to the presence of pyrite in the mine spoils (Schaaf and Hüttl,
490 2005; Rivas-Pérez et al., 2016).

491

492 *3.4.4. Electrical conductivity is very high in some SAZ types*

493 The electrical conductivity (EC) data are scarce (Tables 1 and 2) as this parameter was
494 mainly measured in soils where high EC values were expected (Table SI-3f). In most of
495 the SAZ types, the EC range was not different from that of the reference soils and was
496 always lower than 2 mS cm⁻¹ which is the limit for non-saline soils (Baize, 2000;
497 Schoeneberger et al., 2002). With EC above this threshold, saline soils represent 3.4 % of
498 soils worldwide according to the FAO (www.fao.org). However, in 20 % of urban and
499 mining soils, EC higher than 2 mS cm⁻¹ were recorded and EC values exceeding 4 mS cm⁻¹
500 were encountered in about 15 % of the cases. Some soils reached extremely high EC
501 (≥ 16 mS cm⁻¹), in relation with the salinization observed in Northern cities like Chicago
502 (Scharenbroch and Catania, 2012) or Moscow (Nikiforova et al., 2014) due to the use of
503 salt for deicing roads and the concentrated drainage observed at some metal mine sites
504 (Pellegrini et al., 2016). At depth, high EC was observed only for mining soils (Table SI-
505 3f).

506

507 *3.4.5. CEC is rarely measured in SAZs*

508 CEC was measured in only 12% of the studies (Tables 1 and 2), resulting in the absence

509 of data for some SAZs or some soil types, notably for deep horizons (Table 2). If one
510 considers the soil with CEC larger than $6 \text{ cmol}^+ \text{ kg}^{-1}$ (which is a low value if fertility is
511 considered), there is no difference between the SAZs and the reference soils with the
512 exception of the 10 % of traffic soils on allochthonous materials and 10 to 20 % of the
513 mining soils on allochthonous materials or undefined. However, these CECs were
514 measured for the fraction less than 2 mm, which in the case of soils on allochthonous
515 materials may represent a rather small fraction of the whole soil because of their high
516 stoniness as mentioned above.

517

518 4. Synthesis and recommendations

519 Among the different SAZs, more data on pedological characteristics are available in the
520 literature on urban, mining or recreational soils than on industrial and traffic soils. The reason
521 behind this lower representation of industrial and traffic soils is probably their partial
522 inclusion in urban soils as very often only the mention “soil sampled in an urban area” is
523 reported in the articles. Care should be taken to better describe the land use in SAZ studies. In
524 addition, despite their surficial abundance (70 % of the artificial surfaces) only a few studies
525 have focused on sealed soils, which were therefore not considered in this synthesis. However,
526 the few existing studies showed that sealed soils can store a substantial amount of SOC
527 (Raciti et al., 2012), despite the decrease in the SOC stock in the first years after sealing (Jim
528 et al., 1998b; Wei et al., 2014). The amount of organic carbon stored in sealed soils, and the
529 potential importance of its role, have not been sufficiently investigated to draw general
530 conclusions and more studies dedicated to this soil type should be performed.

531 For unsealed soils, we showed that different soil types are encountered, ranging from only
532 slightly disturbed soils to Technosols on allochthonous material, the latter being the most

533 abundant in the literature. Studies often focus on disturbed areas, but it remains necessary to
534 assess urban land surfaces with natural or little disturbed profiles for functions such as
535 supporting urban food production.

536 We also showed that both the soil profile type and the land use determine the
537 pedological characteristics of SAZs. While inherent characteristics are strongly linked to
538 the type of soil profile, with allochthonous soils being richer in coarse elements and
539 poorer in $< 2 \mu\text{m}$ fractions, manageable characteristics are linked either to land use (the
540 case of pH), or to both land use and soil type (the case of organic carbon or bulk density).
541 Here again, the frequent absence of descriptions of soil profiles prevents a detailed
542 understanding of the determinants of the acquisition of their pedological characteristics.
543 In addition, the characterization SAZs is mainly limited to their surface horizons
544 (topsoils) and not enough studies have been conducted on subsoils. Drawing
545 conclusions from our set of data for deep horizons is thus more difficult. This highlights
546 the need for a more systematic study of soil profiles. The articles reporting information
547 at depth point to the importance of subsoils in fulfilling some ecosystem services such as
548 carbon storage as already observed in natural soils (Balesdent et al., 2018) or, on the
549 contrary, preventing water infiltration.

550 Lastly, not all soil characteristics are investigated systematically. As observed from the
551 102 papers in the database, some parameters were either too seldom reported (e.g. total
552 soil depth) or with too various methods (e.g. nutrients, pH other than water pH) to be
553 included for discussion in this analysis. Some parameters were discussed but in a limited
554 number of studies (e.g. % coarse elements, EC and CEC).

555 To take advantage of future data to be produced on SAZs and thus improve their
556 characterization, we suggest that the following points should be systematically

557 addressed:

558 - the history of the soil formation by systematically associating data on land use,
559 historical background, demographic growth, economic growth, and typology of uses, to
560 the studied profiles;

561 - the whole soil profile must be considered when characterizing the soil physicochemical
562 properties on well-defined horizons;

563 - the use of a common set of sampling and analytical methods and a common typology of
564 the technogenic materials present in soils;

565 - assessment of the representativeness and the spatial extension of the reported points
566 or profiles, in the same way as it is usually performed for agricultural or forest soils.

567

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574

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884 **List of figure captions**

885 Figure 1: Evolution over time of the number of studies included in the database for the
886 different SUITMAs. Papers including several SUITMAs are counted once per SUITMA,
887 which explains the discrepancy between the number of papers included in the database
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889

890 Figure 2: Origin of the studies of the database per SUITMA. Papers including several
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895 Figure 3: Land-cover of the reference soils in the database (n=83)

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897 Figure 4: Distribution of the soil classification of the soils of artificialized zones
898 contained in the database (n=561)

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900 Figure 5: Examples of artificialized soil profiles: a) Soil from a mine tailing: earthy
901 material on spoil (TC, M); b) succession of gravel and earthy layers on concrete (TC, T);
902 earth material on top of a natural profile (AT, U/R); c) Superposition of earthy material
903 on a technogenic material (TC, U/R); d) multiple layers of alternate earthy and
904 technogenic material (TC, U); e) succession of backfilling material, earthy material and
905 granular material embedding a pipe (TC, U/T); f) Soil from a mine tailing: earthy
906 material on spoil (TC, M); g) earthy material on red mud (TC, I); h) Joint soil and
907 partially sealed soil (TC, U).

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909 Figure 6: Two first factors of the CA performed on the different soil types of the different
910 SAZs and reference soils for the different parameters: a- coarse elements (CE); b- < 2 μ m
911 fraction; c- bulk density; d- soil organic carbon; and e- water pH for the topsoil (0-0.1, 0-
912 0.2 or 0-0.3 m depending on the study). Ellipses represent the AHC performed on the
913 two first factors of the CA.

914

915 Figure 7: Two first factors of the CA performed on the different soil types of the different
916 SAZs and reference soils for the different parameters: a- coarse elements (CE); b- < 2 μ m
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919 first factors of the CA.

920

921 **List of table captions**

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924 for recreational; Indust, for industrial; Mine, for mining; Nat., for natural vegetation and
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931

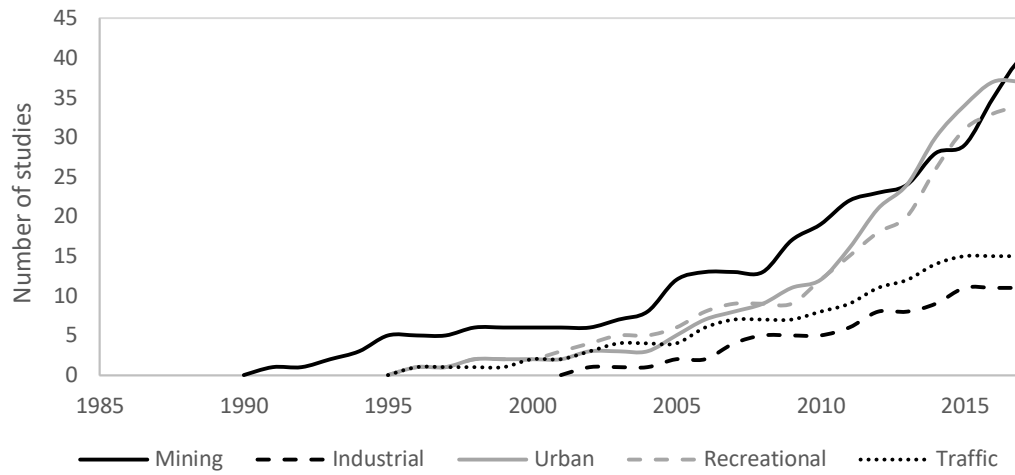


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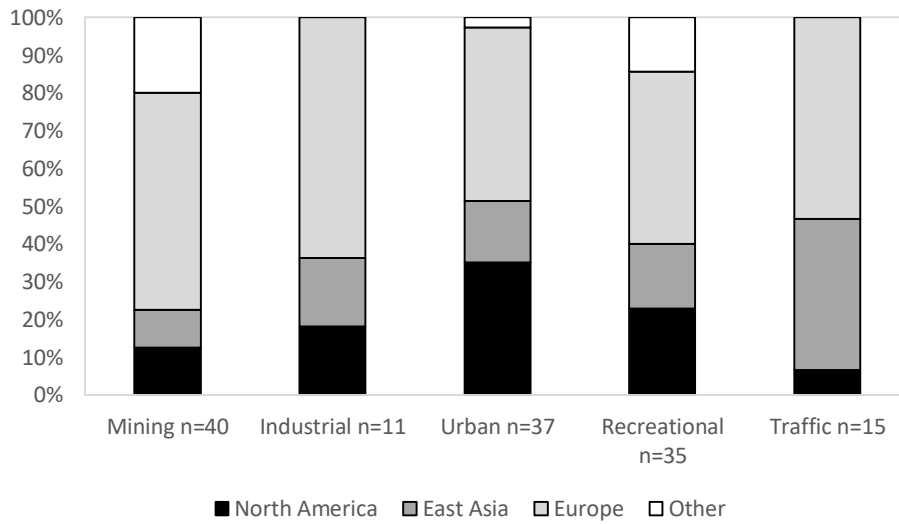


Figure 2: Origin of the studies of the database per SUITMA. Papers including several SUITMAs are counted once per SUITMA, which explains the discrepancy between the number of papers included in the database (n=102) and the number of studies recorded for the different SUITMAs (n=138).

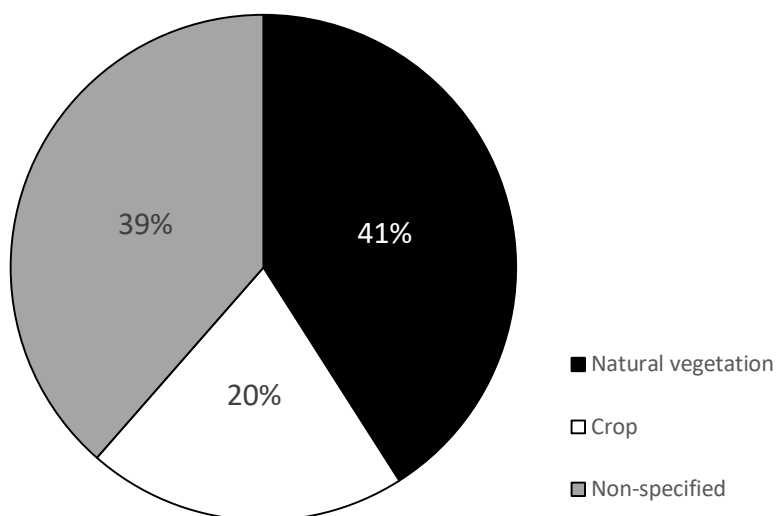


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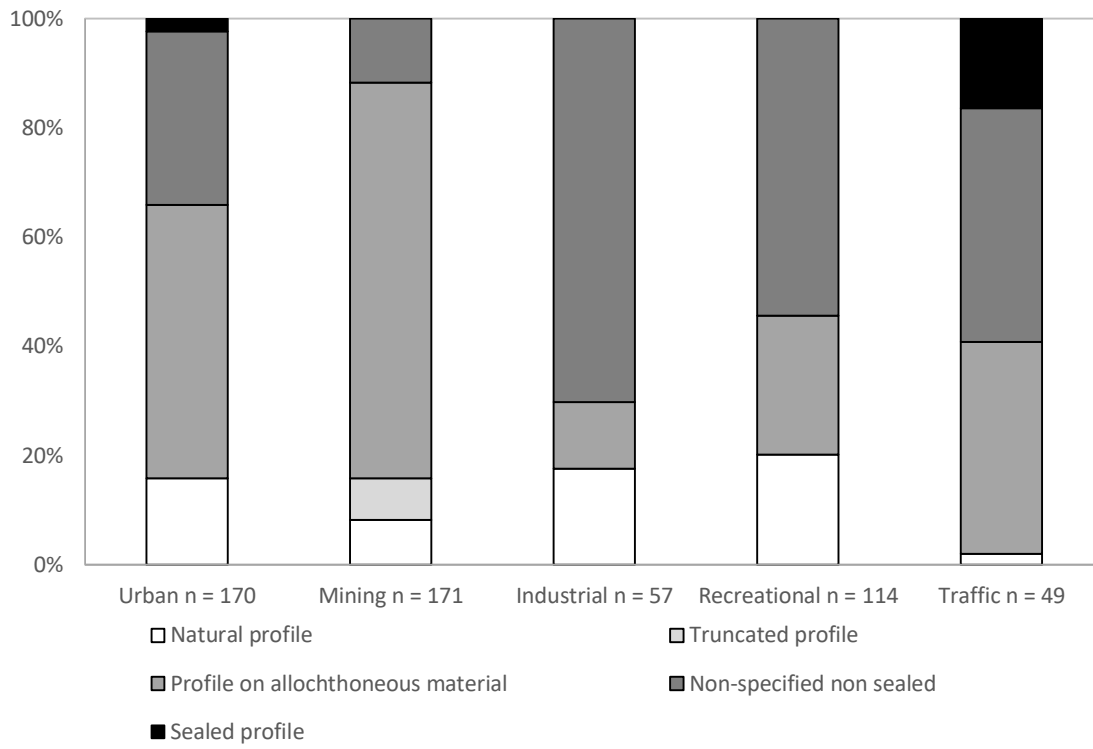


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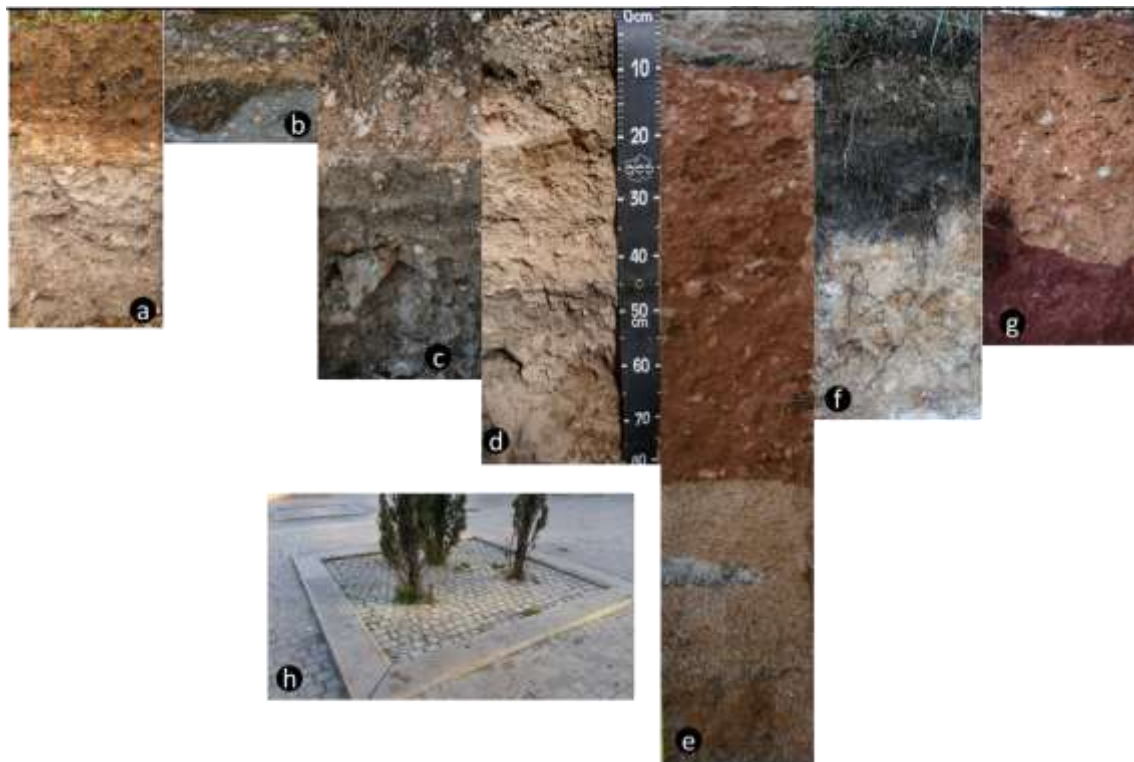


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Figure 6: Two first factors of the CA performed on the different soil types of the different SAZs and reference soils for the different parameters: a- coarse elements (CE); b- < 2 μm fraction; c- bulk density; d- soil organic carbon; and e- water pH for the topsoil (0-0.1, 0-0.2 or 0-0.3 m depending on the study). Ellipses represent the AHC performed on the two first factors of the CA.

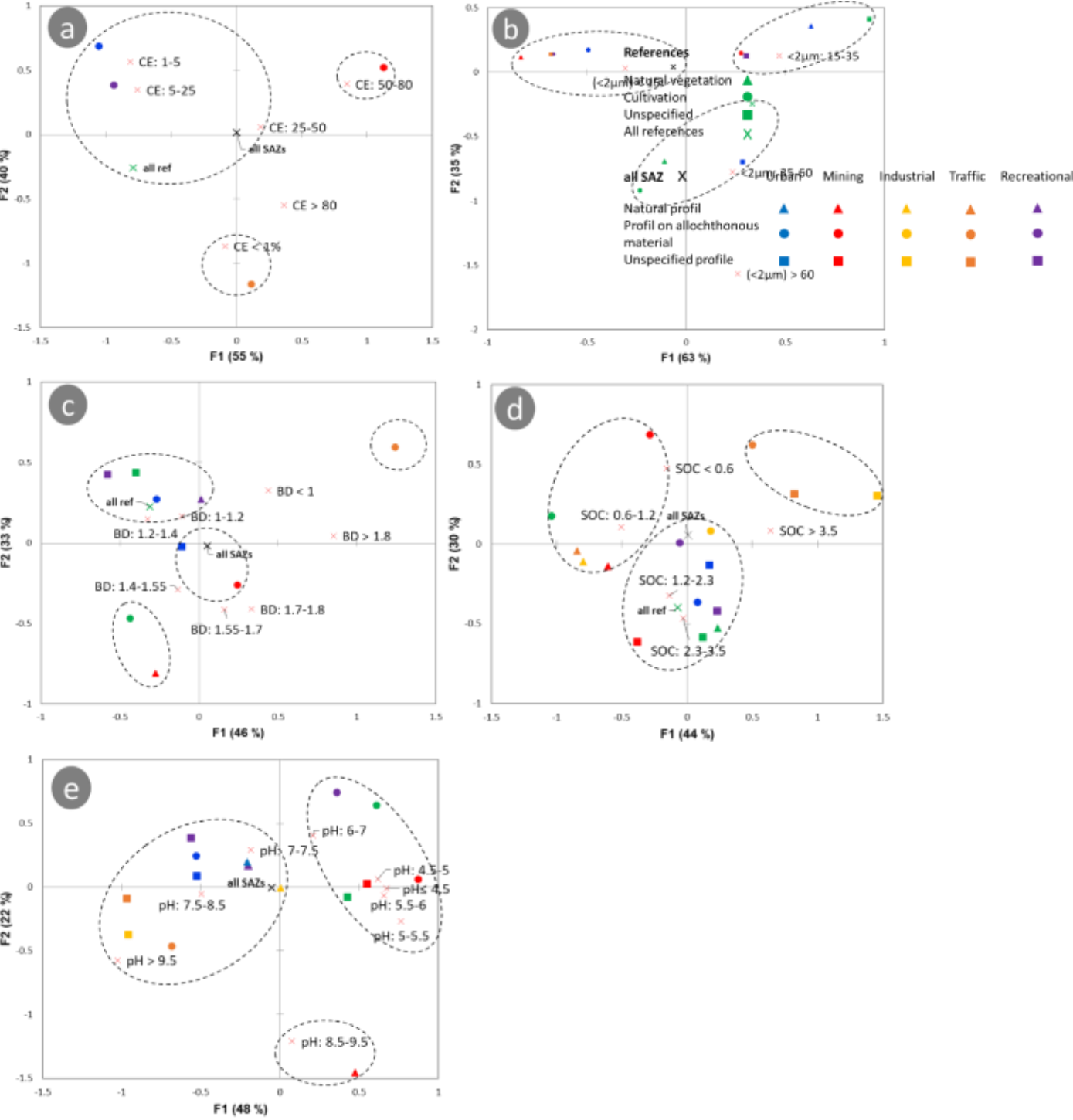


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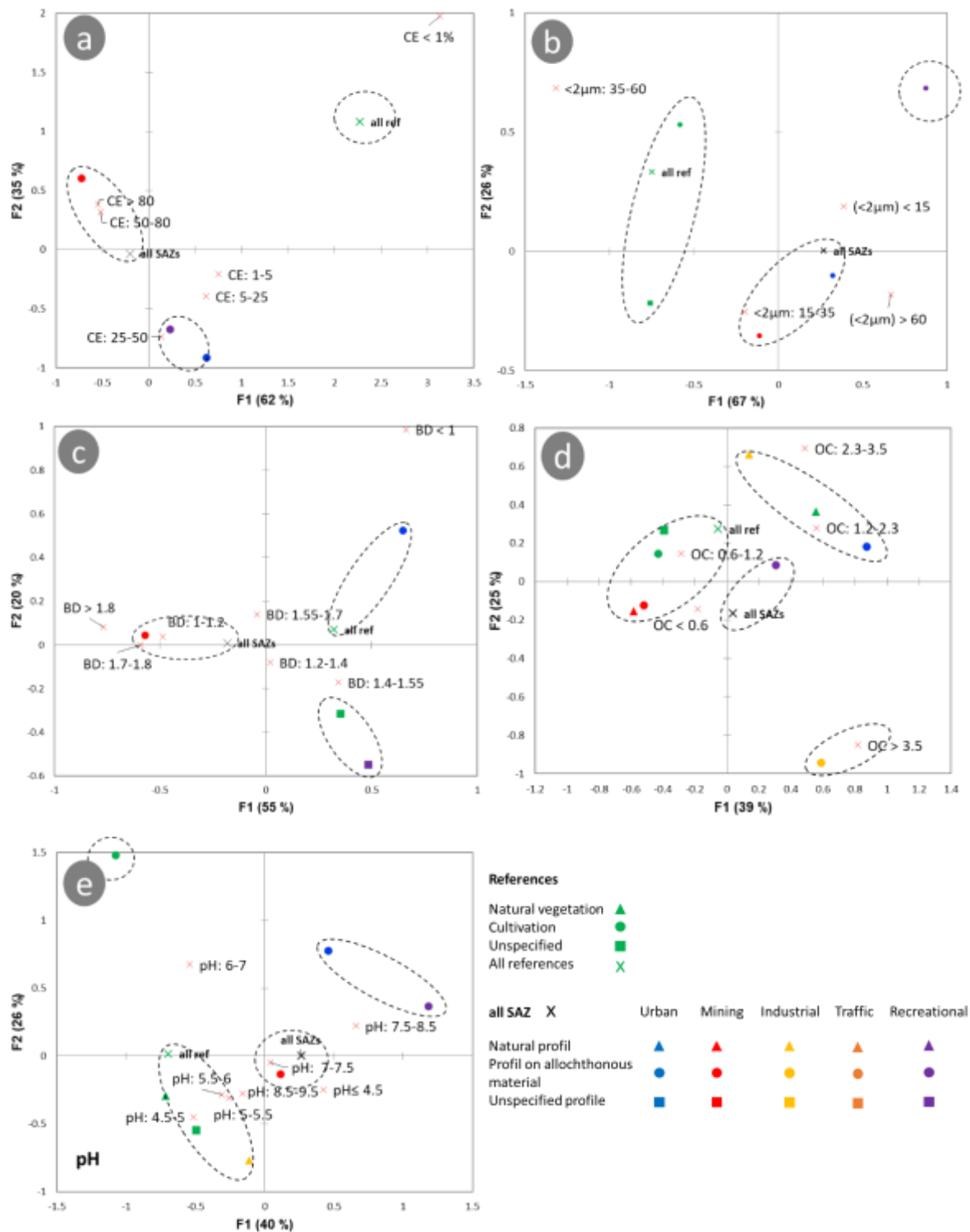


Table 1 : Number of topsoils (0-30 cm) in the data base for each considered soil property, each soil type and each land use (Tot, stands for total; Urb, for urban; Recre, for recreational; Indust, for industrial; Mine, for mining; Nat., for natural vegetation and Unsp., for unspecified vegetation).

	Tot	<i>Urb</i>	<i>Recre</i>	SAZ			References			
				<i>Indust</i>	<i>Traffic</i>	<i>Mine</i>	Tot	<i>Nat.</i>	<i>Crop</i>	<i>Unsp.</i>
pH										
sealed	5									
Natural profile	69	14	16	10	0	29	64	20	11	33
Profile on										
allochthonous materials	184	52	18	6	13	95				
Unspecified profile	158	47	35	36	15	25				
Total	416	113	69	52	28	149				
SOC										
sealed	1									
Natural profile	55	12	21	2	0	20	63	27	13	23
Profile on										
allochthonous materials	183	46	26	22	22	67				
Unspecified profile	171	56	53	30	18	14				
Total	410	114	100	54	40	101				
Bulk density										
sealed	2									
Natural profile	28	5	8	0	0	15	31	7	10	14
Profile on										
allochthonous materials	113	20	6	2	15	70				
Unspecified profile	72	41	24	2	5	0				
Total	215	66	38	4	20	85				
< 2 µm										
sealed	2									
Natural profile	29	13	6	0	0	10	39	10	11	18
Profile on										
allochthonous materials	123	31	26	0	3	63				
Unspecified profile	66	25	18	4	14	5				
Total	220	69	50	4	17	78				
Coarse elements										
sealed	1									
Natural profile	2	2	0	0	0	0	5	2	3	0
Profile on										
allochthonous materials	49	8	9	0	15	17				
Unspecified profile	2	1	1	0	0	0				
Total	54	11	10	0	15	17				
Cation Exchange Capacity										
sealed	0									
Natural profile	9	0	4	0	0	5	8	2	3	3
Profile on										
allochthonous materials	66	10	9	0	10	37				
Unspecified profile	40	28	2	0	0	10				
Total	115	38	15	0	10	52				
Electrical conductivity										
sealed	1									
Natural profile	16	6	9	0	0	1	13	2	1	10
Profile on										
allochthonous materials	53	14	1	0	0	38				
Unspecified profile	43	10	3	19	1	10				
Total	113	30	13	19	1	49				

Table 2 : Number of subsoils (> 0.4 m) in the data base for each considered soil property, each soil type and each land use (Tot, stands for total; Urb, for urban; Recre, for recreational; Indust, for industrial; Mine, for mining; Nat., for natural vegetation and Unsp., for unspecified vegetation).

	Tot	<i>Urb</i>	<i>Recre</i>	SAZ			Tot	References		
				<i>Indust</i>	<i>Traffic</i>	<i>Mine</i>		<i>Nat.</i>	<i>Crop</i>	<i>Unsp.</i>
pH										
sealed										
Natural profile	18	2	4	8	0	4	37	10	9	18
Profile on										
allochthonous materials	75	11	9	1	2	52				
Unspecified profile	22	7	3	1	4	7				
Total	115	20	16	10	6	63				
SOC										
sealed										
Natural profile	14	1	4	0	0	9	41	15	10	16
Profile on										
allochthonous materials	72	15	10	11	2	34				
Unspecified profile	14	5	6	0	3	0				
Total	100	21	20	11	5	43				
Bulk density										
sealed	0									
Natural profile	3	2	0	0	0	1	19	3	3	13
Profile on										
allochthonous materials	44	11	6	3	5	19				
Unspecified profile	12	2	8	0	2	0				
Total	59	15	14	3	7	20				
< 2 µm										
sealed	0									
Natural profile	6	1	0	0	0	5	24	4	8	12
Profile on										
allochthonous materials	67	18	9	0	0	40				
Unspecified profile	12	1	3	1	2	5				
Total	85	20	12	1	2	50				
Coarse elements										
sealed	0									
Natural profile	0	0	0	0	0	0	5	2	3	0
Profile on										
allochthonous materials	37	8	9	0	5	15				
Unspecified profile	0	0	0	0	0	0				
Total	37	8	9	0	5	15				
Cation Exchange Capacity										
sealed	0									
Natural profile	7	0	4	0	0	3	7	2	3	2
Profile on										
allochthonous materials	41	10	9	0	0	22				
Unspecified profile	5	0	1	0	0	4				
Total	53	10	14	0	0	29				
Electrical conductivity										
sealed	0									
Natural profile	1	0	0	0	0	1	4	1	1	2
Profile on										
allochthonous materials	36	3	1	0	0	32				
Unspecified profile	14	1	0	9	0	4				
Total	51	4	1	9	0	37				