

The historic man-made soils of the Generalife garden (La Alhambra, Granada, Spain)

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Summary

We studied the soils of the Patio de la Acequia garden of the Generalife, a palatial villa forming part of La Alhambra, a World Heritage Site in Granada, Spain. This garden, which is estimated to be around 700 years old, is the oldest historical garden in the Western World. The soils are man-made cumulimollic-humic-calcaric (hypereutric, anthric) Regosols. Noteworthy amongst the main pedogenic processes, in relation to the human activities of cultivation, irrigation and tillage, are horizonation, melanization (the contents of organic carbon varied between 0.59% and 8.87%, and those of P₂O₅ extracted with citric acid between 723 mg kg⁻¹ and 7333 mg kg⁻¹, with maximae in the Ap horizons) and structure formation. The soil fabric, studied at the ultramicroscopic level using scanning electron microscopy, is of laminar and partition-walls' type in the lower horizons, depending on the microped zones. The partition-walls' fabrics found are different to those of the possible pre-existing sedimentary fabrics. These are numerous lithological discontinuities and at least two burials, leading us to deduce that there have been two main stages of filling with materials in the formation of these soils. The first is Arabic-Medieval (13th century), when the garden was created, its surface being some 50 cm below the level of the paved area of the present patio. In the deeper parts, the materials employed in the fill are similar to the *in situ* soils of the zone, unaffected by the buildings. The second stage is Christian (15th century to the present day). During this period the Medieval garden was gradually buried under a layer of materials from the nearby soils and/or sediments mixed with manure until the surface was only just below the level of the paved area of the patio. In this work we discuss the difficult classification of these relatively little studied soils. In spite of their being clearly related to human activity, they are not classified as Anthrosols in the FAO system (1998) because soil materials cannot be classified as anthropopedogenic or as anthropogeomorphic.

Historical introduction and objectives

'A garden is a highly personal thing to many people – a part of home. They go a long way toward making soils right for this plant and that.'

This quote from Charles E. Kellogg's classic book *Our Garden Soils* (Kellogg, 1952) illustrates the close relationship between people and their garden soils while implying that the history of the latter may enable us to better understand the history of the former. Garden soils (including those of parks) are a highly significant type of urban soil (De Kimpe & Morel, 2000) with important functions since gardens have tradition-

ally been used for both ornamental purposes and for the cultivation of fruit and vegetables for human consumption. One very specific type is those gardens belonging to historic buildings, which we shall call historical gardens; these generally have an ornamental or recreational purpose, although certain areas may be used for food production. Despite the importance of garden soils, very few detailed studies have been carried out on them, especially in areas with a Mediterranean climate, and no studies at all have been found for the soils of historical gardens. The study of such soils may be important for soil scientists, as well as archaeologists and historians.

The palace complex of La Alhambra, incorporating the Generalife, forms part of the city of Granada (Spain) (Figure 1), is one of the most popular tourist attractions in the world, and

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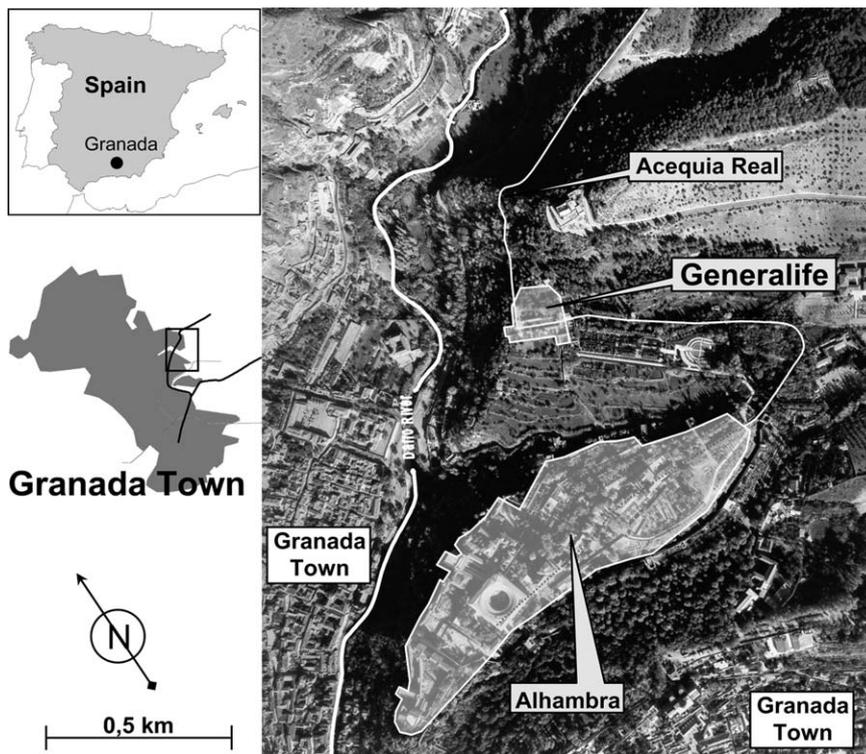


Figure 1 Location of study area (Generalife), including the 'Acequia Real' (irrigation channel).

has been declared a World Heritage Site. It was built by Spanish Muslims from the 11th century onwards, reaching its most splendid point during the 14th and 15th centuries under the dynasty of the Nazaries. The Nazari Kingdom of Granada ended in 1492 when the territories were reconquered by the Spanish monarchs known as the 'Catholic Kings', Isabel I and Fernando V. La Alhambra (*sensu strictum*) was a palace city; a walled community containing a military zone, palaces for the aristocracy and workshops for artisans. On the other hand, the Generalife was a large palatial villa with a recreational role, situated next to the walls of La Alhambra.

Both complexes (La Alhambra and Generalife) contain historical gardens that have inspired poets, painters and writers with their beauty. Of all these gardens the most important is the Patio de la Acequia of the Generalife, forming the central nucleus of the palatial villa (Figure 2). This was created at the end of the 13th century and is today the oldest ornamental garden in the Western World, with the additional value of never having ceased to be a garden during the last seven centuries (Casares-Porcel *et al.*, 2004a). The name and original nature of the Patio de la Acequia are due to the 'Acequia Real', a channel that supplies water to the Generalife. The Acequia Real runs longitudinally through the patio; water is a vital component of the patio, both for irrigation of the garden and as decoration.

As a result of the lack of information from the Medieval period nothing is known of the origin of the Generalife or when it was built. Although the primitive 'almunia' (farmhouse) may date from the Almohad period (12th century) (Vilchez, 1991),

the presence of gardens would have depended on the availability of water. As there are no natural springs in this zone, the presence of gardens in the Generalife is due to the construction of the Acequia Real. According to contemporary accounts this channel was built during the reign of Muhammad I (1238–1272), the founder of the Nazari dynasty (Ibn al-Jatib, 1998). Thus, the first buildings and gardens date from the first half of the 13th century.

However, the only concrete information on the early gardens is from the archaeological excavations carried out in the Patio de la Acequia (Bermudez-Pareja, 1965), which show that the garden was divided into four rectangular beds with a central arbour. This layout has remained virtually unchanged to the present day (Figure 2).

A previous palynological study coordinated with the current study (Casares-Porcel *et al.*, 2004b) has revealed that the soil contains pollen of ornamental species, even in the deepest horizons, suggesting the continuous presence of a garden for ornamental purposes. Amongst the plants cultivated were laurels (*Laurus nobilis*), cypresses (*Cupressus sempervirens*), citrons (*Citrus limon*), orange trees (*Citrus aurantium*), pomegranate trees (*Punica granatum*), myrtles (*Myrtus communis*), ivy (*Hedera helix*), jasmine (*Jasminum* sp.), vines (*Vitis vinifera*) and several types of rose (*Rosa* sp.), none of them being native.

The aim of the current study is to characterize the soils of the garden of the Patio de la Acequia of the Generalife (Granada), hitherto unstudied and a good example of historical garden soils. Consequently, a detailed pedological study of these soils was carried out, including the study of their genesis and their

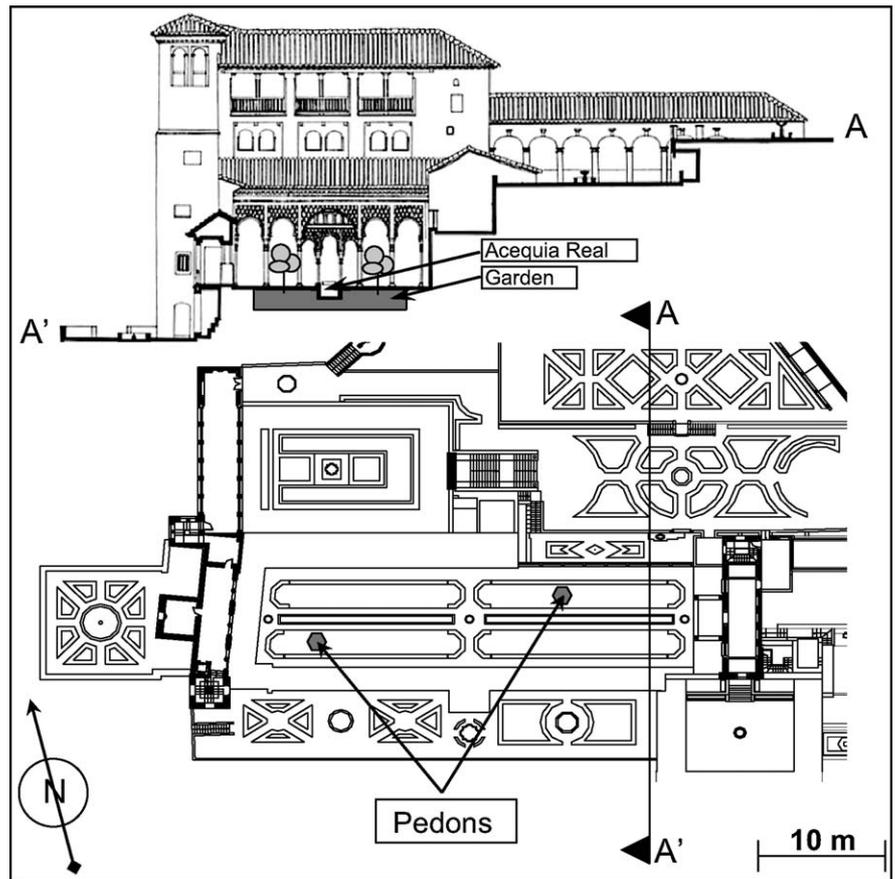


Figure 2 Section (A-A') and floor of the Generalife Palace, showing the garden of the 'Patio de la Acequia' and the sample locations.

classification according to FAO (1998) and Soil Taxonomy (Soil Survey Staff, 2003). Another objective was to reconstruct the history of the garden using the pedological data obtained.

Materials and methods

Setting

La Alhambra is situated at 798 m above sea level in an area of moderately steep, low ridges, crowned with plateaux, which descend towards the River Darro and the neighbouring city of Granada (Figure 1). The landscape is shaped from heterometric conglomerates of metamorphic pebbles and cobbles (mostly micaschists, quartzites, amphibolites) and a sandy matrix belonging to the Alhambra Formation (Lupiani *et al.*, 1985). The climate is Mediterranean, with annual rainfall of 480 mm and mean annual temperature of 15.3°C. The soil temperature regime is thermic and the moisture regime xeric (Soil Survey Staff, 2003). The potential vegetation is oak forest (*Paenion-Querceto rotundifoliae s.*), although, due to the effects of past human activity, this is severely degraded and only relics of the climax formation remain. The whole area of La Alhambra and Generalife currently receives special protection. The most representative native soils of the zone are Alfisols: Ultic Vertic Palexeralfs (Delgado *et al.*, 1990).

Sampling

The Acequia Real of the Patio de la Acequia garden (Figure 2) runs longitudinally through the patio, forming the centrepiece of a rectangular garden of 48.7 × 12.8 m and dividing the garden into two roughly rectangular halves. Two pedons (P1 and P2), representative of each of these halves, were excavated (a minimal volume of the pedon, surface area 1 m², due to the special protection regime) and sampled. Disturbed soil materials from each horizon were collected. Unaltered soil aggregates were directly sampled in the profile with Kubiena-boxes. All materials were air-dried before analysis.

Current soil management & water regime

Information on current soil management was compiled through a survey of the gardeners. Tillage is carried out by hand in autumn, spring and summer. A range of fertilizers is applied: animal manure (sheep, cow, goat) in autumn, inorganic fertilizer (N, P and K, in the ratio 15, 15, 6) and iron chelates (occasionally added).

The soils are irrigated by flooding, generally during the summer deficit (c. 400 mm) and whenever the vegetation requires it. Irrigation frequency suggests a contribution of around 2000 mm of water year⁻¹. For this reason, at the moment of sampling (25 February 2000), all the soil profiles were saturated

with water. Under these conditions the moisture regime of the two garden soils sampled is udic (Soil Survey Staff, 2003) (Figure 3).

Methods

The morphological features of the soils (Table 1) were described in detail according to FAO (1990). A redness ratio index (RI = $(25 - n_{\text{hue}}) \times \text{chroma}/\text{value}$) was calculated from the dry Munsell colours (Martín-García *et al.*, 1998).

Granulometric analysis was carried out by sieving and sedimentation (pipette method; Soil Conservation Service, 1972); the clay and fine sand were selected for mineralogical study.

The rock fragments of each horizon were assessed for shape, degree of weathering and rock type. Fine gravel-size human artefacts were also studied. This fraction was chosen as it involved handling reasonable quantities of soil for the results to be representative.

Other properties determined in the < 2 mm fraction were as follows (Soil Conservation Service, 1972): soil water release, pressure membrane apparatus; organic carbon, dichromate oxidation; total nitrogen, Kjeldahl method; P₂O₅, Olsen method and soluble in 1% citric acid; electrical conductivity (EC) in an extract 1:1.5 (w:w) soil:water; pH, 1:1 suspension of fine earth:water; CaCO₃ equivalent, Bernard's calcimeter; exchangeable Ca²⁺, Mg²⁺, Na⁺ and K⁺, cation exchange capacity (CEC) and base saturation, with ammonium acetate (pH 7) and sodium chloride, and determination by atomic absorption spectrophotometry (AAS); free iron, citrate-dithionite extract (Holmgren, 1967) and AAS; and microelements, DTPA extract (Lindsay & Norvell, 1978) and AAS.

Total content of Ca, Ti and Zr in the fine earth was determined by X-ray fluorescence (XRF) (Phillips PW 1404).

X-ray diffraction (XRD) traces of the fine earth, fine sand and clay fractions were obtained using a Philips PW 1730 diffractometer, Cu K α radiation, 35 kV, 15 mA, scan speed 2°2 θ minute⁻¹, time constant 2 s. Oriented aggregates of clay fractions were

prepared by sedimentation and drying on glass slides, using a variety of treatments (Brown & Brindley, 1980; García-González & Sánchez-Camazano, 1968). Semi-quantitative estimates of proportions of minerals were made on the basis of intensity factors (Delgado *et al.*, 1982). The width at half height ($^{\circ}2\theta$) (WHH) in the mica-illite 1.0 nm peak was measured to estimate crystallinity (Kübler, 1968).

The ultramicrofabric of selected samples was studied by scanning electron microscope (SEM; Hitachi S-510) in natural and fresh cut surfaces of air-dried, unaltered soil aggregates. The sample was fixed to an aluminium sample holder using colloidal silver glue and then metallized with Au. The features studied and the terminology used were taken from Yong & Warkentin (1975) and Smart (1979).

Results and discussion

General and morphological characteristics

Both P1 and P2 possess a complex sequence of horizons (Table 1) due to changes in the parent materials (lithological discontinuities), burials, fill materials and tillage. In contrast to P1, in P2 there is a 3AC3 horizon containing a pocket of materials (horizon 2AC2) with which it is in contact laterally; this pocket may be the result of the presence of an old tree, subsequently lost, and infilled. In P2 there is also a thin buried Ah horizon, as shown by its smaller dry and wet chromas, small RI and its granular structure, with respect to the horizons with which it is in contact. Both P1 and P2 contain a buried C horizon (4Cb of P1 and 5Cb of P2) in the deep parts of the profile.

In both soils the colours of the upper parts are black, very dark brown and very dark greyish brown; this could indicate continuous processes of organic fertilization. The colour becomes redder (redder hue) or more chromatic (chroma increases) in the deepest horizons of both profiles (dark reddish brown in 4Cb of P1 and brown-dark brown in 5Cb of P2); concordantly, the RI index shows the maximum values (Table 1).

Stains of different colour are frequent in P1 and P2 for a variety of reasons: (i) in the superficial parts (Ap1, Ap2) these stains are zones enriched with organic matter from manuring; (ii) in the intermediate horizons (AC) the stains seem to originate from the mixing of materials from the horizons above and below as a result of the intense human activity that these soils have undergone during their history (digging, tillage, replacement of trees and bushes, infilling of holes, watering, etc.) as well as the bioturbation caused by earthworms; (iii) in the lower horizons (C), the most reddish stains suggest provenance from the dominant material of the neighbouring native Palexeralfs (hue 2.5 YR, value 3.5, chroma 6) (Delgado *et al.*, 1990), remnants of which have remained at the base of the garden soil.

The cutans described at the base of P1 and in the 2AC horizon of P2 are clayey and are always minor features.

The large numbers of roots and the abundant signs of biological activity due to earthworms, including the coprogenic

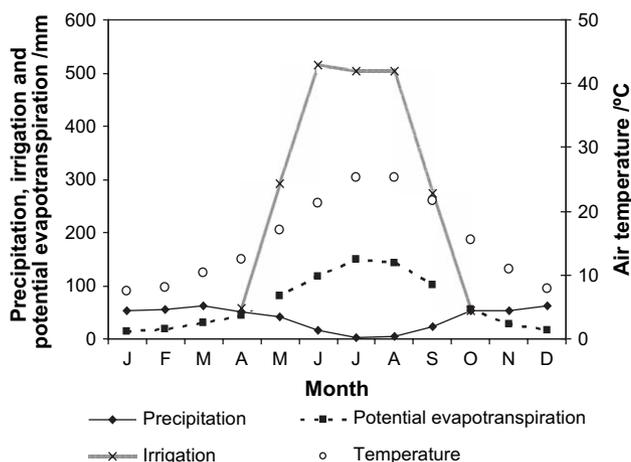


Figure 3 Water balance (including irrigation) of soil P1.

Table 1 Morphological characteristics of the profiles

Horizon	Depth /cm	Munsell colour					RI ^a	Colour stains (dry)	Rock fragments ^b	Structure ^c	Consistency ^d	Cutanic features ^e	Voids ^f	Roots ^g	Biological features ^h	Horizon boundary ⁱ	Human artefacts ^j
		Dry	Moist	Wet													
P1 Ap1	0–8	10YR 3/2	10YR 2/1	10YR 2/1	3.3	black (manure)	sr, f, mc-qz-scr	mo, me-co, gr	sha, fi, sst, pl	–	fi-me, ma	fe, fi	ND	c, w	br+bo+sh+pl+me		
Ap2	8–14	10YR 5/3	10YR 3/2	10YR 3/3	3.0	black (manure)	sa, f, mc-scr-qz	mo, co, sb,*	sha, fr, sst, spl	–	vfi-fi, ma ewc	fe, fi	m, b+ca	c, w	br+bo+sh+pl+me+gl		
AC1	14–20	10YR 4.5/3	10YR 3.5/2	10YR 3.5/2	3.3	ND	sr, f, mc-qz-scr	mo-st, co, ab	ha, fr, st, pl	pf	coa-fi-vfi, com	com, fi	c, b+ca	g, s	br+bo+sh+gl		
AC2	20–30	10YR 3/3.5	10YR 3/2	10YR 3/2	5.8	10R–2.5YR 4/6	sr, w, mc-qz-scr	st, co, ab,*	ha, fr, st, pl	pf	fi, com	com,fi; fe,me; fe,coa	f, ca	g, w	br+bo+sh		
2AC3	30–39	10YR 5/4	10YR 4/3	10YR 4/3	4.0	5YR 4/6	sa, w, mc-qz-(scr)	mo-st, me, ab	vha, vfr, vst, vpl	–	fi, com	com,fi; fe,me; fe,coa	ND	g, w	br+bo+sh		
3C	39–92	7.5YR 4/4.5	7.5YR 3/3	7.5YR 3/3	8.4	2.5YR 4/6	sa, w-s, mc-qz-(scr)	mo-st, me, ab,*	eha, vfr, sst, pl	–	–	n	c, b+ca	g, s	br+bo		
4Cb ^k	> 92	5YR 4/4.5	5YR 3/4	5YR 4/6	11.3	2.5YR 4/6	sa, w-s, mc-qz-(scr)	mo, me, ab	ha, vfr, vst, vpl	c, vo	fi, fe	n	ND	–	br+bo		
P2 Ap1	0–5	10YR 3/2.5	10YR 2/2	10YR 2/2	4.2	black (manure)	sr, f, mc-qz-scr	st, co, gr	sha, fi, sst, pl	–	fi-me, ma	fe, fi	m, b+ca	a, s	br+bo+sh+pl+me+gl		
Ap2	5–15	10YR 3/2	10YR 2/2	10YR 2/2	3.3	black (manure)	sr-sa, f, mc-qz-scr	mo, co, sb,*	vha, fr, sst, spl	–	fi-me, com ewc	fe, fi	m, b+ca	c, s	br+bo+sh+pl+me+gl		
AC1	15–30	10YR 5/3	10YR 3/2	10YR 3/3	3.0	ND	sa, w, mc-qz-scr	mo-st, me-co, sb-ab	vha, vfi, vst, vpl	–	fi-me, fe ewc	com,me; fe,coa	c, b	g, s	br+bo+sh+pl		
2AC2 ^l	30–63	10YR 3/3.5	10YR 3/4	10YR 3/6	5.8	10R–2.5YR 4/6	sa, w, mc-qz-(scr)	st, co, ab	ha, fr, st, pl	c	vfi	fe, me	ND	c, b	br+bo		
3AC3	30–63	7.5YR 4/4	7.5YR 3/3	7.5YR 3/3	7.5	ND	sr-sa, w, mc-qz-(scr)	mo-st, vc, ab	vha, fr, st, vpl	–	fi, fe	fe, me	c, b+ca	c, s	br+bo		
4Ahb	63–68	7.5YR 4/3	7.5YR 3/3	7.5YR 3/2	5.6	5YR 4.5/4	sr, w, mc-qz-(scr)	mo-st, co, sb-gr,*	ha, fr, vst, pl	–	fi, fe	vfe, fi	c, ca	g, s	br+bo+sh		
5Cb	> 68 (+86)	7.5YR 4/6	7.5YR 4/3	7.5YR 4/3	11.3	10R 4/6	sr, w-s, mc-qz-(scr)	st, vc, sb	so, fr, sst, pl	–	coa, ma	n	ND	–	br+bo		

^aRI = (25-n_{hue}) × (chroma/value); calculated from the dry Munsell colours.

^bShape: a = angular; sa = subangular; sr = subrounded. Weathering: f = fresh or slightly weathered; w = weathered; s = strongly weathered. Nature: mc = micaschists; qz = quartzite; scr = sedimentary carbonate rocks – limestone and dolostone (in brackets when very few).

^cGrade: mo = moderate; st = strong. Size: me = medium; co = coarse; vc = very coarse. Type of structure: sg = single grain; gr = granular; ab = angular blocky; sb = subangular blocky. * = coprogenic earthworm structure detected.

^dWhen dry: so = soft; sha = slightly hard; ha = hard; vha = very hard; eha = extremely hard. Consistency when moist: vfr = very friable; fr = friable; fi = firm; vfi = very firm. Stickiness: sst = slightly sticky; st = sticky; vst = very sticky. Plasticity: spl = slightly plastic; pl = plastic; vpl = very plastic.

^eNature: c = clay; pf = pressure faces. Location: vo = voids.

^fSize: vfi = very fine; fi = fine; me = medium; coa = coarse; vc = very coarse. Abundance: fe = few; com = common; ma = many. ewc = earth worm channel.

^gAbundance: n = no roots; vfe = very few; fe = few; com = common; ma = many. Size: fi = fine; me = medium; coa = coarse.

^hAbundance: m = many; c = common; f = few. Kind: b = burrows (earthworms); c = casts (earthworms).

ⁱDistinctness: a = abrupt; c = clear; g = gradual. Topography: s = smooth; w = wavy; b = broken.

^jFine gravel (2–5 mm): Pieces of: br = brick; bo = animal bone; sh = shell; pl = plastic; me = metal; gl = glass.

^kContains remains of materials of a reddish argillic horizon related to soils of the Alhambra Formation (Delgado *et al.*, 1990).

^lPocket of materials without lateral continuity.

ND, not detected.

structure described in the Ap2 horizons, should also be noted.

The presence, throughout both profiles, of artefacts resulting from human activity (pieces of brick, animal bone, shell, plastic, metal, glass) is noteworthy. In the lower parts of the profiles (C horizons) brick and bones mainly appear. On ascending the profile, the types of artefacts become more diverse. All the material types appear in the Ap horizons, including plastics, which are undoubtedly from the 20th century. This could be used as an indicator that the soil has been constructed from the bottom upwards with the passing of time.

Soil structure and ultramicrofabric study

At the macroscopic level, the soil structure (Table 1) shows moderate development, with a majority of horizons, both in P1 and P2, moderately structured and some strongly structured

(horizon AC2 of P1; horizons Ap1, 2AC2 and 5Cb of P2). The types of structure detected are granular, and angular and sub-angular blocks although there are also cases where a biological contribution (coprogenic) is evident; the presence of peds in the form of earthworm excreta is evident in horizons Ap2, AC2 and 3C in P1, and Ap2 and 4Ahb in P2.

The fabrics detected by SEM (Figure 4) are clearly differentiated, with several hierarchical levels of fabric units ordered by size, from the most basic and smallest, domains, to the largest, micropeds, passing through the intermediate unit of clusters. Their pedogenic origin will be discussed later. The phyllosilicate domains are of fine silt and clay size ($< 10 \mu\text{m}$). The clusters are composed of a grouping of domains and can be found in our samples in various hierarchical levels. Furthermore, they have different morphologies and sizes depending on the type of horizon and the zone of the microped studied.

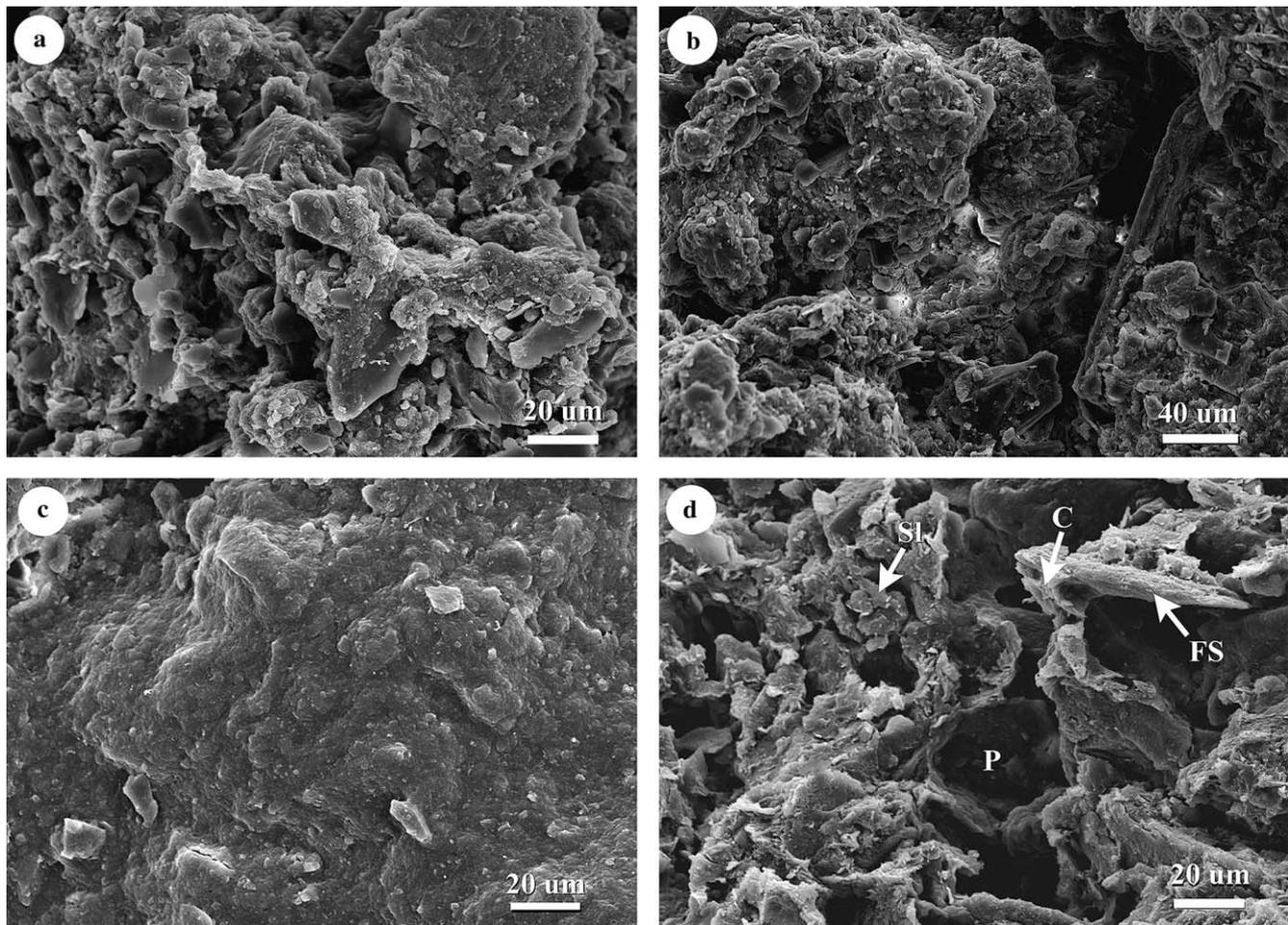


Figure 4 SEM images of soil ultramicrofabric. (a) Profile 1, Ap2. Interior of microped. Skeletal-cemented fabric. Spheroidal clusters between 20 and $100 \mu\text{m}$ in size. (b) Profile 1, Ap2. Exterior of microped. Skeletal-cemented fabric. Spheroidal clusters between 50 and $100 \mu\text{m}$ in size. (c) Profile 1, 4Cb. Exterior of micropeds. Anisotropic laminar fabric. (d) Profile 1, 4Cb. Interior of micropeds. Partition-walls fabric. In the centre of the cells there are pores of $20\text{--}50 \mu\text{m}$ diameter (P). Cementing between particles can be seen (C). Mineral grains of fine sand (FS) and, above all, silt (SI) can be observed.

In both profiles, the upper horizons, Ap1 and Ap2, show (Figure 4a,b) spheroidal clusters with a size of between 50 and 100 μm (ocasionally up to 200 μm). The fabrics are skeletal-cemented types with skeletal grains of the silt fraction (frequently particles $> 10 \mu\text{m}$) and calcareous and organic cements, as a result of the large content of all these components in these horizons (Tables 2 and 3); the porosity is noteworthy, being both inter- and intrafabric units. These voids appear as a result of several factors, including: packing between particles and/or structural units, flocculation/cementation of the particles by colloids, and biological activity. This would explain the variety of void shapes and sizes; quasi-circular to irregular (predominant) for the former and from $< 0.5 \mu\text{m}$ to $> 100 \mu\text{m}$ for the latter. Void abundance was estimated at around 30%.

Both in P1 and P2, in the lower horizons (AC, C and Ahb) the fabrics of the interior and exterior of the micropeds can be differentiated: (i) at the surface (Figure 4c), they are laminar with phyllosilicate domains oriented parallel to the microped surface (anisotropic laminar fabric); (ii) in the interior (Figure 4d), the face-to-face joins of laminar domains of clay and fine silt ($< 10 \mu\text{m}$) give rise to laminar clusters (there may be several hierarchical levels; that is, these are, in turn, formed by smaller laminar clusters) which are somewhat curved, like partition-walls, and between 20 and 100 μm and 5–10 μm thick; the laminar clusters, by means of face-to-edge joins, form partition-wall fabrics that are reminiscent of a honeycomb (Smart, 1979), although not analagous. The spaces defined by the par-

tion-walls may remain hollow, appearing as pores of 20–50 μm (Figure 4d). In these lower horizons, the clays, iron forms and, to a lesser extent, carbonates, all of which are present (Table 3), seem to play an active part in the formation of these fabrics (laminar and partition-walls), fulfilling the role of cements between the particles.

Analytical characteristics

The soil horizons are loamy (loam, silty loam and clayey sandy loam) (Table 2). The percentages of gravel tend to increase with depth.

In the upper horizons, the values for available water are small, bearing in mind the amounts of organic carbon (Table 3) and the well-developed structure. This may be due to the value for retained water, 33 kPa, being small. To explain this phenomenon would require, at least, a detailed study of the organic material and porosity relationships, which is beyond the scope of this work.

The organic carbon and total nitrogen contents (Table 3) tend to decrease with depth in both profiles. This is due to the decrease in organic material, generally added as surface manuring. This tendency is interrupted in P2 by the presence of an Ahb horizon. This finding is similar to that of Sandor & Eash (1995) in old soils, terraced by man, in Peru, where there are buried Ah horizons. The degree of evolution of the humus is difficult to interpret from the C/N values as both organic carbon and nitrogen are added regularly in fertilizer.

Table 2 Selected physical properties of the fine earth fraction ($< 2 \text{ mm}$)

Soil	Horizon	Particle size distribution /%									Water retention ^b /%		
		Coarse fragments ^a		Fine earth ($< 2 \text{ mm}$)							33 kPa	1500 kPa	AW /mm cm ⁻¹
		FG (2–5 mm)	Total ($> 2 \text{ mm}$)	Sand					Silt	Clay			
VC	C	M	F	VF									
P1	Ap1	12	12	4.4	4.9	5.0	8.9	8.9	48.3	19.6	33.6	29.2	0.56
	Ap2	4	11	4.5	5.3	4.7	7.9	9.9	47.4	20.3	32.2	23.6	1.14
	AC1	17	22	5.3	6.1	5.9	9.5	11.0	40.0	22.2	28.3	16.2	1.44
	AC2	5	14	3.8	3.8	3.7	5.8	7.5	56.7	18.7	27.4	13.7	1.85
	2AC3	18	21	4.7	5.6	5.3	8.7	10.7	41.1	23.9	23.0	11.9	1.24
	3C	5	25	6.6	7.6	7.3	12.7	11.8	27.4	26.6	20.3	10.7	1.16
	4Cb	17	44	7.3	8.7	8.9	15.8	13.5	21.6	24.2	16.8	9.4	0.65
P2	Ap1	3	11	4.9	6.6	6.4	10.6	8.8	39.7	23.0	33.6	24.8	1.16
	Ap2	12	13	6.0	6.3	6.1	10.1	9.4	40.1	22.0	29.4	24.7	0.62
	AC1	3	11	5.8	6.3	5.7	8.9	8.9	42.5	21.9	25.1	14.1	1.53
	2AC2	5	12	4.3	5.0	5.1	9.7	11.4	37.7	26.8	26.4	13.5	1.74
	3AC3	3	24	6.8	9.0	3.4	14.8	12.2	28.9	24.9	18.9	9.6	1.16
	4Ahb	8	41	5.9	8.7	9.0	14.1	11.5	26.9	23.9	22.8	11.4	1.06
	5Cb	6	23	7.4	8.4	8.3	13.8	11.1	25.5	25.5	18.7	10.4	1.02

FG = fine gravel; VC = very coarse sand (1000–2000 μm); C = coarse sand (500–1000 μm); M = medium sand (250–500 μm); F = fine sand (100–250 μm); VF = very fine sand (50–100 μm); AW = available water.

^aPercentages refer to whole soil.

^bPercentages refer to weight.

Table 3 Selected chemical properties of the fine earth fraction (< 2 mm)

Soil Horizon	OC			N		C/N		P ₂ O ₅ /mg kg ⁻¹		pH		CaCO ₃ eq.		Exchangeable bases/ cmol _c kg ⁻¹				Elemental composition (XRF)							
	OC	%	—	N	%	—	C/N	Olsen	Citric acid	EC/S m ⁻¹	EC/S m ⁻¹	pH	CaCO ₃ eq. /%	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CEC /cmol _c kg ⁻¹	Fe ₂ O ₃ CD	CaO /%	TiO ₂	Zr /mg kg ⁻¹	Molar TiO ₂ /ZrO ₂	Molar CaO/ZrO ₂	
P1	Ap1	8.35	0.57	15	1331	7333	0.216	7.3	23.4	58.8	5.8	0.6	4.7	27.3	1.06	15.66	0.48	148.9	24	78.5					
	Ap2	7.76	0.54	14	1189	6291	0.254	7.1	25.3	34.4	5.4	0.6	4.4	24.3	1.39	15.75	0.49	150.5	24	781					
	AC1	3.32	0.22	15	598	4474	0.126	7.6	22.1	49.3	4.1	0.3	1.6	17.0	1.64	14.84	0.56	174.2	24	636					
	AC2	1.49	0.12	12	495	1609	0.081	8.0	18.9	31.3	4.4	0.2	1.0	17.9	1.83	12.83	0.61	178.8	25	535					
	2AC3	1.67	0.10	17	373	854	0.058	8.0	14.0	39.1	7.6	0.1	0.9	17.9	2.05	9.58	0.74	201.0	27	356					
P2	3C	0.84	0.08	11	371	880	0.043	7.9	3.8	20.3	4.7	0.1	0.7	15.2	2.47	5.36	0.78	234.0	25	171					
	4Cb	0.59	0.03	20	330	1088	0.029	8.2	1.2	21.0	5.9	0.1	0.6	12.8	2.73	2.47	0.91	269.7	25	68					
	Ap1	8.87	0.57	16	1274	7177	0.140	7.2	15.6	35.4	3.6	0.2	2.1	26.8	1.43	13.48	0.58	166.2	26	605					
	Ap2	7.13	0.51	14	1329	7281	0.158	6.9	18.6	23.4	4.4	0.2	2.2	25.3	2.01	12.99	0.57	163.0	26	595					
	AC1	2.52	0.17	15	534	4292	0.060	8.0	17.7	31.9	6.1	0.2	0.9	18.3	2.09	11.78	0.62	179.9	26	489					
3AC3	2AC2	1.74	0.10	17	392	723	0.037	8.3	4.7	24.7	6.1	0.2	1.0	19.7	2.45	8.97	0.72	218.2	25	307					
	3AC3	0.96	0.07	14	399	984	0.040	8.1	5.7	28.2	4.5	0.1	0.5	15.1	2.76	4.63	0.90	239.8	28	144					
	4Ahb	2.89	0.10	29	456	1270	0.035	8.0	6.4	37.7	5.7	0.1	0.6	20.1	1.25	5.58	0.86	233.1	28	179					
5Cb	0.84	0.05	17	389	802	0.023	8.1	10.8	27.6	4.9	0.1	0.6	16.6	3.06	6.78	0.79	226.7	26	223						

OC = organic carbon; N = total nitrogen; EC = electrical conductivity; CaCO₃ eq. = calcium carbonate equivalent; CEC = cation exchange capacity; Fe₂O₃ CD = iron oxide extracted with citrate-dithionite; XRF = X-ray fluorescence.

The contents of P₂O₅ (Table 3) are large, especially those extracted by citric acid, which is typical of irrigated crops with contributions of organic manures and biomaterials rich in phosphates such as bones and shells (Kaufman & James, 1991), which we found in the fine gravel. Consequently, the maximum values are found in the Ap and AC horizons. The increase in the 4Ahb horizon of P2 is once again the result of being an old Ah horizon. In horizon 4Cb of P1, there is also an increase in P₂O₅ extracted with citric acid, which might indicate a buried soil, although there is no increase in organic carbon content.

Electrical conductivity is very small in all the horizons, although slightly greater at the surface, possibly as a result of the fertilizer. The low conductivity reflects leaching by the irrigation water, which is of good quality (Patronato de La Alhambra-Generalife, personal communication).

The calcium carbonate equivalent exhibits relatively greater values in the superficial horizons, with irregular variations between horizons, decreasing in the lower horizons. The increase in carbonates in the upper parts of the soil may be due to: (i) the materials recently employed in the construction of the garden contained carbonates; (ii) the manure contains carbonates; or (iii) the water for irrigation of the garden is from the mountains close to the Sierra Nevada range and flows for several kilometres over calcareous rocks. Repeated irrigation would thus lead to an increase in carbonates in the upper parts (in fact, the fountains in the patio have accumulations of carbonate deposits).

The small quantities of CaCO₃ equivalent in the lower part of P1 may once again be due to the relation between this material and the native soils of the zone, which are decarbonated (Delgado *et al.*, 1990).

The exchange complex is saturated in bases, the most abundant exchange cation being Ca²⁺, followed by Mg²⁺, closely followed by K⁺, and, finally, Na⁺. This sequence is typical of the soils of the region (Pérez-Pujalte & Prieto, 1980), which probably provided the materials for the construction of the garden. The rather high values of K⁺ are probably due to the fertilizing process.

The Fe₂O₃CD shows moderate values (1.06–3.06%) that increase with soil depth, except in the 4Ahb horizon of P2, where the values decrease in a similar way to those of the upper Ap horizons (further evidence that this horizon is a buried Ah). A significant relationship was found between %Fe₂O₃ CD (Table 3) and RI (Table 1): RI = 3.61 × (%Fe₂O₃ CD) – 1.58, n = 14, r = 0.771 (P < 0.01), showing the pigmentation effect of the iron forms on soil colour.

Microelements in < 2 mm soil

These elements appear to be concentrated in the Ap horizons and, to a lesser extent, in the AC1 (Table 4). This may be due to the addition of organic and inorganic fertilizers (even chelates), insecticides or pesticides and to the biogeochemical cycle of these elements.

Table 4 Selected microelements extracted by DTPA solution in the fine earth fraction (<2 mm)

Soil	Horizon	Copper	Cobalt	Chromium	Manganese	Nickel	Iron	Zinc	Aluminium
		/mg kg ⁻¹							
P1	Ap1	2.72	0.12	0.04	12.00	0.76	34.1	11.80	0.40
	Ap2	2.32	0.10	0.04	10.60	0.72	30.7	12.00	0.22
	AC1	2.24	0.06	0.02	4.00	0.68	18.1	8.24	0.20
	2AC2	1.92	0.04	0.02	2.72	0.38	9.8	4.72	0.14
	2AC3	1.60	0.04	0.02	2.16	0.50	8.2	2.56	0.26
	3C	1.48	0.06	0.02	2.40	0.36	7.6	2.24	0.04
	4Cb	0.92	0.06	ND	1.60	0.30	5.4	1.76	ND
P2	Ap1	2.56	0.12	0.04	11.20	0.76	35.2	13.00	0.20
	Ap2	2.40	0.12	0.04	10.60	0.82	34.9	12.40	0.18
	AC1	2.56	0.06	0.02	3.60	0.54	15.1	6.56	0.04
	2AC2	2.40	0.06	0.02	1.76	0.42	12.6	2.64	0.12
	3AC3	1.20	0.06	0.02	2.24	0.44	8.6	1.44	0.18
	4Ahb	2.32	0.08	0.02	2.40	0.38	13.3	3.28	0.28
	5Cb	1.32	0.08	0.06	1.84	0.30	8.3	1.84	0.20
Mean		2.00	0.08	0.03	4.94	0.53	17.3	6.03	0.19
Standard deviation		0.58	0.03	0.01	4.11	0.19	11.3	4.53	0.10

ND, not determined.

In urban soil, and particularly in garden soils, given their proximity to sources of emission, levels of microelements are usually higher than in agricultural or natural soils (Morel *et al.*, 2005). But when the quantities extracted with DTPA in our soils are compared with the mean values obtained by Adriano (2001) for soils from around the world, Cr, Mn and Co (except in the Ap1 and Ap2 horizons of both profiles) and Ni are present in lesser quantities in our soils; however, Mn and Co (in the Ap1 and Ap2 horizons) and Cu present normal values while Zn presents large values in all the samples. None of the elements analysed in our soils exceed the critical toxicity values established (Adriano, 2001) for the main crops, our values being somewhat less than those for Anthrosols cultivated for vegetables in China (Zhang *et al.*, 2003); for example, the Cu content for soils in China was around 10 mg kg⁻¹, as opposed to < 3 mg kg⁻¹ in the Generalife soils. Furthermore, if we compare our results with those obtained by Bech *et al.* (1998) in Alfisols from the northeast of Spain, the values of Cu, Ni and Zn are similar to those of our soils.

The small concentrations of these microelements in our soils may be due to our gardens being sufficiently distant from the city of Granada. Furthermore, there is little industry in Granada and the historic site of La Alhambra is very carefully managed.

Mineralogical analysis

In the fine sand and fine earth fractions of both profiles (Table 5), XRD revealed quartz, plagioclases, potassium feldspar, calcite, dolomite, goethite, haematite and phyllosilicates: chlorite, micas (illite and paragonite) and kaolinite.

Phyllosilicates are the most abundant mineral component of the fine earth. In both profiles the proportions of phyllosilicates

in the most superficial horizons (Ap1, Ap2, AC1, AC2 in P1; Ap1, Ap2, AC1 in P2) are close to, generally below, 50%; the lower horizons of both profiles, developed over other parent materials (2AC3, 3C, 4Cb in P1; 2AC2, 3AC3, 4Ahb, 5Cb in P2) show proportions of phyllosilicates in the fine earth above 50% and sometimes over 60%.

Quartz is an abundant mineral component, being relatively most concentrated in the fine sand fraction; the greatest values are found in the P2 horizons. Other abundant components are the carbonates, calcite (most abundant) and dolomite, especially in the upper zones of the profile, as detected chemically (Table 3). The most abundant form of iron is goethite, due to the significant presence of organic matter and the frequent wetting of the soils during irrigation (Schwertmann & Taylor, 1989).

The phyllosilicate mineral species present were examined in more detail in the oriented aggregate XRD-diagrams of the clay fractions, confirming and/or revealing the presence of chlorite, illite (most abundant), paragonite, kaolinite, smectite (abundant) and interstratified minerals (a mixture of mica and swelling phyllosilicates). The illite is especially noteworthy because a small but not very systematic increase was detected in the WHH values (Table 5) from the upper horizons to the lower. This indicates that illite is relatively more degraded in the deep parts of the profile, although in no case is the peak at 1.0 nm clearly asymmetric.

Smectite content in the clay fraction decreases in the lower parts of the profiles, mainly in the lower horizons 4Cb of P1 and 5Cb of P2. This may be due to the relationship between these horizons and the native soils of the area as the proportion of smectite in the latter is never greater than 18% and is frequently below 10% (Delgado *et al.*, 1990).

Table 5 Mineralogical composition (XRD, %) of selected granulometric fractions

Soil	Horizon	Fine earth (< 2 mm)							Fine sand (0.25–0.05 mm)							Phyllosilicates of the clay fraction (< 0.002 mm)						
		Qz	Fd	Phyll	Cal	Dol	Goe	Hem	Qz	Fd	Phyll	Cal	Dol	Goe	Hem	Ch	Il	Pa	Ka	Sm	Int ^a	Illite WHH ^b /°2θ
P1	Ap1	16	1	47	24	9	2	1	22	6	29	20	20	2	1	6	55	5	8	23	3	0.45
	Ap2	18	1	38	23	17	1	2	29	7	23	17	23	1	0	5	64	2	7	20	2	0.44
	AC1	16	1	53	17	10	2	1	37	0	22	18	23	0	0	5	62	1	7	23	2	0.39
	AC2	28	1	42	17	8	1	3	35	7	28	18	12	0	0	6	47	tr	9	38	tr	0.43
	2AC3	24	2	52	14	5	4	2	49	12	23	13	0	3	0	6	51	3	8	32	tr	0.47
	3C	17	2	57	14	4	4	2	45	1	22	20	12	0	0	5	62	2	7	18	6	0.53
	4Cb	29	1	62	3	1	4	tr	49	7	40	1	0	3	0	5	68	2	7	8	10	0.47
P2	Ap1	17	1	49	21	9	2	1	45	5	11	20	19	0	0	6	60	1	8	20	5	0.43
	Ap2	15	1	44	16	21	3	tr	38	2	18	21	21	0	0	5	66	2	8	17	2	0.42
	AC1	22	1	49	17	9	2	tr	40	1	21	25	13	0	0	6	60	2	8	22	2	0.37
	2AC2	15	6	58	12	7	2	tr	32	2	17	29	20	0	0	7	56	1	10	21	5	0.52
	3AC3	26	1	64	6	tr	3	tr	56	9	17	12	6	0	0	7	63	2	9	16	3	0.46
	4Ahb	26	1	57	11	tr	5	tr	69	6	18	5	0	2	0	7	64	2	10	15	2	0.48
	5Cb	20	1	65	10	1	3	tr	57	3	25	10	0	2	3	9	59	2	13	12	5	0.50

Qz = quartz; Fd = feldspars (K-feldspars and plagioclases); Phyll = phyllosilicates (illite, paragonite, kaolinite, interstratified minerals and chlorite); Goe = goethite; Hem = haematite; Ch = chlorite; Il = illite; Pa = paragonite; Ka = kaolinite; Sm = smectite; Int = interstratified minerals; tr = trace.

^aSwelling phyllosilicate-mica phases (band between 1.0 and 1.4 nm).

^bWidth at half-height of the 1.0 nm illite peak.

Lithological discontinuities and burials

We have placed special emphasis on: (i) the evidence indicated by Soil Taxonomy (Soil Survey Staff, 2003), which considers lithological discontinuities as diagnostic soil characteristics; (ii) colour (Waltman *et al.*, 1990); (iii) the classic molecular ratios CaO/ZrO₂ (Beavers *et al.*, 1963) and TiO₂/ZrO₂ (Chapman & Horn, 1968); (iv) mineral contents (phyllosilicates in the fine earth, smectite in clay); (v) quantities and types of human artefacts; (vi) lateral changes of soil horizons (the case of the transition from 2AC2 to 3AC3 in P2); and (vii) for the detection of buried horizons, laboratory data such as organic carbon percentages and P₂O₅ contents. From the joint application of all these criteria, we established three lithological discontinuities in P1 and four in P2 (Table 6). We consider as certain those cases in which several of the criteria coincide; we also found two burials: in P1 at 92 cm in the 4Cb horizon and in P2 at 63 cm in the 4Ahb horizon.

The CaO/ZrO₂ and TiO₂/ZrO₂ molar ratios are of interest. The CaO/ZrO₂ ratio (Table 3) shows notable changes in both profiles, which we interpret as lithological discontinuities; however, the values tend to decrease towards the deep horizons of both profiles owing to the decrease in carbonate content. We were unable to see any pattern in the TiO₂/ZrO₂ ratio due to the possible relative homogeneity of the quantity of these metals in the anthropogenic materials.

The variability of the soil materials can also be observed horizontally. In spite of the fact that the two pedons studied show a degree of similarity in the majority of the properties studied, some differences were detected, including, for example, horizon

sequence, carbonate contents, quartz content in the fine sand, free iron content, etc. (Tables 2, 3 and 5). These differences demonstrate that the pedons are not identical, although they are only 15 m apart and belong to the same garden. The material employed in the construction of the soils, its history and the transformations undergone, can explain these differences (see below).

Classification

In terms of the FAO (1998) classification, the soils of the Patio de la Acequia garden have the following as diagnostic criteria: (i) a *mollic horizon*, the requirement for colour contrast with respect to the C horizon has been eliminated as this horizon does not exist (only horizon 4Cb in pedon P1 and horizon 5Cb in pedon P2 are present); (ii) *strongly humic properties*; and (iii) a *calcaric soil material*. The presence of a *terric horizon* was discounted as all the soil was formed in various episodes rather than gradually (as detailed in the following section) and the material is relatively homogeneous in texture with depth (Table 2). Neither is the diagnostic horizon a *hortic horizon*, as it does not reach the required 25% of the volume in the form of earthworm casts (FAO, 1998). The material of the horizons 4Cb of P1 and 5Cb of P2 cannot be classified as an *aria anthropogeomorphic soil material*, in spite of the presence of the remains of *Palixeralf* material in these lower horizons, as in no case could the remains be considered as being of an *argic horizon*, nor does this material reach $\geq 3\%$ (by volume) of the mass of the horizons. Furthermore, they show *hyperetric* and

Table 6 Lithological discontinuities and burials in the soils

Profile	Depth /cm	Lithological discontinuities			Burials	
		Horizons that separate	Soil Taxonomy ^a evidence	Other criteria	Horizons that separate	Criteria
P1	30	AC2 from 2AC3	Rock fragment lithology (3): sedimentary carbonate rock content decreases considerably Soil colour (8): reddening decreases (RR index) Laboratory data: CaO/TiO ₂ decreases	Quantity of phyllosilicates in fine earth decreases		
	39	2AC3 from 3C	Soil colour (8): reddening increases (RR index) Laboratory data: CaO/TiO ₂ increases	Shell disappears ^b Quantity of artefacts decreases ^b		
	92	3C from 4Cb	Abrupt textural contacts (1): total gravel content doubles Soil colour (8): reddening increases (RR index)	Quantity of artefacts decreases ^b Quantity of smectite in clay decreases	3C from 4Cb	P ₂ O ₅ citric acid content increases
P2	30	AC1 from 2AC2 and 3AC3	Rock fragment lithology (3): sedimentary carbonate rock contents decreases considerably Laboratory data: CaO/TiO ₂ decreases	Shell and plastic disappear ^b Quantity of phyllosilicates in fine earth decreases		
	30/63	2AC2 from 3AC3	Laboratory data: CaO/TiO ₂ decreases	Quantity of artefacts decreases ^b 2AC2 is a pocket of materials within 3AC3		
	63	2AC2 and 3AC3 from 4Ahb	Abrupt textural contacts (1): total gravel content doubles	Shell reappears ^b Quantity of artefacts increases ^b	2AC2 and 3AC3 from 4Ahb	OC and P ₂ O ₅ content increases Fe ₂ O ₃ CD decreases
	68	4Ahb from 5Cb	Abrupt textural contacts (1): total gravel content decreases drastically Soil colour (8): reddening increases (RR index)	Quantity of smectite in clay decreases		

^aSoil Survey Staff (2003); the number of the order of the criterion established in Keys to Soil Taxonomy is shown in brackets.

^bIn fine gravel.

anthric formative elements, related to the high base saturation and to human influence through tillage, respectively. In these conditions, the Reference Soil Group is *Regosols*, and, at a lower level, they would be *cumulimollic-humic-calcaric (hyper-entric, anthric)*.

According to soil taxonomy (Soil Survey Staff, 2003) they are mineral soil materials, in spite of the relatively large organic carbon content, which is less than 12% in the Ap1 and Ap2 horizons. The mixture of the first 18 cm of P1 and the first 30 cm of P2 satisfies all the conditions required for the *mollic epipedon*. Furthermore, they lack an *anthropic epipedon*, as this requires a regular decrease with depth of P₂O₅ extractable with citric acid and in our case the decrease is irregular (Table 3). The presence of a *mollic epipedon*, saturated in bases, would classify these soils as *Mollisols* in the subgroup *Oxyaquic Hapludoll*. They belong to the *Oxyaquic Subgroup*, as, during the period of frequent irrigation, they are saturated with water

in one or more layers within 100 cm of the mineral surface under non-reducing conditions during at least 20 consecutive days. In fact, when sampled (25 February 2000) the deep parts of the soil were exuding water.

The family name is determined as follows: (i) the particle-size class is *fine-loamy*; (ii) the mineralogy class is *mixed* and not *paramicaceous*, in spite of mica being the most abundant phyllosilicate (Table 5), the mean phyllosilicate content (weighted to the thickness) in the fine sand fraction (0.05–0.25 mm) in the control section of both profiles is 24.5% (P1) and 20.8% (P2) (the lower limit for mica content for the *paramicaceous mineral family* being 25%); and (iii) the soil temperature class is *thermic*, although it could be *mesic* as the mean soil temperature (16.3°C) is close to the *thermic–mesic* boundary (15°C) and the soil temperature was calculated without considering irrigation.

The buried horizons do not change the classification as they are below 50 cm.

Genesis and history of the garden soils

The genesis of the soils studied here is marked first by the fact that they are almost totally constructed by man using fill materials added for the construction of the garden, as shown by the presence of buried horizons and the abundance of lithological discontinuities. This construction seems to have taken place over well-spaced episodes in time. The presence of an Ah horizon buried in P2 (4Ahb, from 63 cm to 68 cm; Table 6) and a buried level in P1 (4Cb, > 92 cm; Table 6) demonstrate the existence of at least two episodes of addition of fill materials.

The frequent lithological discontinuities detected in the profiles (three in P1 and four in P2) indicate heterogeneity in the fill materials. These soils are thus vertically heterogeneous and polycyclic (formed by superimposition of at least two young soils). This feature is common to other urban soils (Morel *et al.*, 1999). Fetzer *et al.* (1998), in garden soils in France and Germany, described a group of well-stratified man-made soils that frequently did not show natural horizons or a buried fossil A horizon in the first metre of the profile, as occurs in our soils. According to these authors, the thickness of the superficial layer, rich in organic material, increases, as does organic carbon content, with increasing age of the garden. This is also described by De Kimpe & Morel (2000). Thus, the large organic carbon contents of our Ap horizons (around 8%), and generally in the profile (easily exceeding 1%), would indicate the great age of the garden (700 years). However, Schleuß *et al.* (1998) obtained organic carbon values of 4.6–4.7% in the Ah horizons (0–54 cm) in a cumuliurbic Anthrosol of a horticultural garden in northern Germany, developed over 1 m of sand and compost in only 20–30 years; in our case the climate may be less favourable for humification or the contributions differed in quantity and quality. However, discussion of this aspect does not form one of the objectives of this study.

The hypotheses of polycyclism and vertical heterogeneity of our soils are supported by the results obtained in the historical, archaeological and palynological analyses carried out in parallel with this study (Casares-Porcel *et al.*, in press), which indicate that during the Middle Ages, that is, during its Arab stage (13th to 15th centuries), the garden was a sunken garden (with respect to its current position), with its surface some 40–50 cm lower than the surrounding paths. This feature is common to many of the Hispano-Muslim gardens, and, in these deep parts, the soils contain medieval pottery and pollen from the plant species cultivated in those times.

In the period following the re-conquest of the Nazari kingdom by the Catholic Kings (1492), the fashion for sunken gardens changed and the patio was filled with new materials, raising the surface to just below the level of the paths. Modern pottery and artefacts have been found in this new material, as has pollen from species cultivated after 1492, many from the Americas (*Bougainvillea*, *Rovinia*, *Opuntia*, etc.) (Casares-Porcel *et al.*, in press). It should be remembered that 1492 not only marked the end of the Nazari kingdom but also the dis-

covery of America by Christopher Columbus. In the layers closest to the surface there is also pollen of plants from the Far East and Africa.

Another interesting genetic problem arises from the lower horizon of both profiles (4Cb of P1 and 5Cb of P2) due to there being some similarities between their properties and those of the neighbouring native, *in situ* soils (*Ultic vertic Palexeralf*, previously studied by Delgado *et al.*, 1990). These include the presence of reddish stains and smaller carbonate and smectite contents in the clay fraction. There are two possible explanations for this: (i) it is the remains of an *in situ* soil that was buried by new materials and, according to the original topography, appeared as the surface at 92 cm in one case (P1) and at 68 cm in the other (P2), the upper limit of the horizons 4Cb of P1 and 5Cb of P2 (Table 1); or (ii) it is a fill carried out with materials from the levelling of the ground and excavations for the construction of buildings and gardens (logically this would be similar to the soils of the area). The second option seems more likely as the material lacks the characteristics of the argillic horizon (present in the *in situ Palexeralfs*). On the other hand, artefacts related to human activity, such as brick and animal bone (Table 1), have been detected, and, even at the level of P1, phosphorus extracted with citric acid increases. The properties and composition of the rest of the soil material (mainly horizons Ap and AC) (Tables 1, 2 and 3) coincide with those of many of the soils from around the city of Granada: loamy textures, calcareous, etc. (Pérez-Pujalte & Prieto, 1980). Unfortunately, there are no old documents, for example from the archives of La Alhambra, that describe the origin of the fill materials that have acted as parent materials of the garden; thus, it is not possible to validate the hypotheses formulated through documental evidence.

The discussion of the genesis of our soils is completed by an analysis of the pedogenic processes that they have undergone. As they are subjected to intensive working, intensive fertilization and irrigation, the general process taking place in these soils has been Anthrosolization (Bockheim & Gennadiyev, 2000). As a result of agricultural activities, including organic fertilization, another detectable process is horizonation of the upper part of the soils (horizons Ap1 and Ap2; Table 1). The accumulation of organic material from manuring (Table 1) also results in there being an active melanization process. This generates a *mollic epipedon*. Consequently, organic carbon, total nitrogen, and phosphorus extracted with citric acid, increase (Table 3). Blume (1989) described the accumulation of humus as a soil-forming process characteristic of the soils generated from deposits in urban agglomerations.

Furthermore, although less clearly, we have detected a crystallochemical process of evolution of the illite in the profile, consisting of an increase in the degradation of the mica from the upper horizons to the lower. This process can be explained in a general way by the fact that the illite derives from the parent material and has a different stability in the soil due to its reacting with the chemical environment (Velde *et al.*, 2003); thus, the mica undergoes a process of pedocrystalchemical

evolution (Martín-García *et al.*, 1998) and is inherited from the soil parent material. The differences between the micas of the different horizons can be explained in more detail as follows: the illites of the upper parts of the profiles would be inherited from sediments added to the soil more recently and thus bearing less degraded illites. On the other hand, the upper horizons contain greater amounts of K^+ in the exchange complex (Table 3), which might imply lesser degradation of the illite.

These soils, in spite of their being constructed, have generated a macroscopically observable soil structure (granular and blocky). In old terraced soils, Sandor & Eash (1995) also described the development of blocky-granular compound structures in cultivated A horizons. According to Blume (1989), structure development is another important soil-forming process characteristic of urban soils formed from deposits. We have described this process by use of SEM. The most highly evolved and interesting SEM ultramicrofabrics are those of the horizons underlying the Ap horizons, which we have named partition-walls fabrics. These fabrics could be compared with honeycomb sedimentary fabrics (Smart, 1979), characteristic of materials with more than 25–30% 2:1 clay type, with cells of 2–3 μm , porosities of 60–90% (Sergeyev *et al.*, 1982) and generated by a process of flocculation and posterior aggregation (van Olphen, 1977). This fabric cannot be confused with ours, even though the proportions of clay or its type or morphological pattern may be similar, because our fabric shows larger fabric units and pedogenic cements (clay, iron forms and carbonates) that are not only shown by SEM images (Figure 4d) but also detected analytically (Table 3). Other possible sedimentary fabrics that may also be present in the original material employed in the construction of the garden, such as skeletal fabric or matrix fabric (Sergeyev *et al.*, 1982), have not been found in our soils. If they were ever present they must have evolved through pedogenesis of the partition-walls' fabric described.

We also found biopedoturbation by earthworms, indicated by, amongst other features, the presence of coprogenic structures (Table 1) or anthropopedoturbation caused by tillage and detected by the presence of stains of materials from different horizons or lateral changes of materials (Table 1).

Finally, in terms of classification, these soils present an interesting series of problems. In FAO (1998) they are *Regosols* rather than *Anthrosols*, in spite of their being closely related to human activities. This is because, in the strict sense, their horizons are not considered to be *anthropedogenic* according to *anthropedogenic processes* (FAO, 1998, p. 31), as they were originally totally constructed soils that later underwent long-term cultivation processes. Their materials cannot be considered *anthropogeomorphic soil material* as they do not match the description of this material (FAO, 1998, pp. 69–70) (such as fragments of diagnostic horizons that are not arranged in any discernible order, organic waste material, earthy material resulting from industrial activities, or containing building rubble and artifacts, etc.) and show features that are the result of

pedogenic processes. Thus, these Regosols cannot be called *anthropic*. Furthermore, modifications due to tillage are excluded for Regosols in the definition of the *anthropic* lower level unit (FAO, 1998, p. 78).

The study by Rossiter & Burghardt (2003) on the groups of urban and industrial soils of the World Reference Base (FAO, 1998) is relevant to the problem of classifying our soils. Due to their agricultural use and the strong human influence they should be considered as Group 2: 'natural soil heavily modified by human use' (mainly Anthrosols). However, this is not possible because they are completely constructed soils. On the other hand, they do not belong to Group 3: 'young soils formed from natural materials moved by human activity' (mainly Anthropogenic Regosols) due to the pedogenesis undergone.

In Soil Taxonomy there is a similar problem as they lack specific diagnostic horizons for man-made soils (for example, an anthropic horizon). Despite being soils that have been heavily modified by man they are classified as Oxyaquic Hapludolls and not in specific taxa like Anthrepts.

We conclude that new revisions of the classifications mentioned should solve the problems related to the classification of man-made soils in historical gardens, either by adapting current taxa or creating new ones. In the case of FAO (1998), we suggest that the definition of the anthropopedogenic horizons should be revised so that the horizons of our soils satisfy the conditions required and can be classified as Anthrosols. In addition, we recommend the inclusion of a new diagnostic property referring to the nature of this type of soil, found at historic sites and subjected to use and cultivation over relatively long periods of time.

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References

- Adriano, D.C. 2001. *Trace Element in Terrestrial Environments: Biogeochemistry Bioavailability, and Risk of Metals*. Springer-Verlag, New York.
- Beavers, A.H., Fehrenbacher, J.B., Johnson, P.R. & Jones, R.L. 1963. CaO-ZrO₂ molar ratios as an index in weathering. *Soil Science Society of America Proceeding*, **27**, 408–412.
- Bech, J., Tobías, F.J., Roca, N. & Rustullet, J. 1998. Trace elements in some Mediterranean red soils from the NE of Spain. *Agrochimica*, **42**, 26–40.
- Bermúdez-Pareja, J. 1965. El Generalife después del incendio de 1958. *Cuadernos de la Alhambra*, **1**, 9–39.

- Blume, H.P. 1989. Classification of soils in urban agglomerations. *Catena*, **16**, 269–275.
- Bockheim, J.G. & Gennadiyev, A.N. 2000. The role of soil forming processes in the definition of taxa in Soil Taxonomy and the World Soil Reference Base. *Geoderma*, **95**, 53–72.
- Brown, G. & Brindley, G.W. 1980. X-ray diffraction procedures for clay mineral identification. In: *Crystal Structures of Clay Minerals and X-Ray Identification* (eds G.W. Brindley & G. Brown), pp. 305–359. Monograph No 5. Mineralogical Society, London.
- Casares-Porcel, M., Tito-Rojo, J. & Cruces-Blanco, E. 2004a. El jardín del Patio de la Acequia del Generalife (I). Su evolución en la documentación escrita y gráfica. *Cuadernos de la Alhambra*, **39**, 63–86.
- Casares-Porcel, M., Tito-Rojo, J. & Socorro-Abreu, O. 2004b. El jardín del Patio de la Acequia del Generalife (I). Consideraciones a partir del análisis palinológico. *Cuadernos de la Alhambra*, **39**, 87–108.
- Casares-Porcel, M., Tito-Rojo, J. & Cruces-Blanco, E. (in press) The garden of the Patio de la Acequia of the Generalife. In: *Handbook of Garden Archaeology* (ed. M. Conan). Dumbarton Oaks, Washington DC.
- Chapman, S.L. & Horn, M.E. 1968. Parent material uniformity and origin of silty soils in northwest Arkansas based on zirconium-titanium contents. *Soil Science Society of America Proceeding*, **32**, 265–271.
- De Kimpe, C.R. & Morel, J.L. 2000. Urban soil management: a growing concern. *Soil Science*, **165**, 31–40.
- Delgado, R., Barahona, E., Huertas, F. & Linares, J. 1982. Los Molisoles de la cuenca alta del río Dilar (Sierra Nevada). *Anales de Edafología y Agrobiología*, **41**, 59–82.
- Delgado, R., Párraga, J., Huertas, F. & Linares, J. 1990. Genèse d'un sol fersiallitique de la Formation Alhambra (Granada, Espagne). *Science Du Sol*, **28**, 53–70.
- FAO 1990. *Guidelines for Soil Profile Description*, 3rd edn (revised). Soil Resources, Management and Conservation Service, Land and Water Development Division, FAO, Rome.
- FAO 1998. *World Reference Base for Soil Resources*. World Soil Resources Report 84, FAO, Rome. At: <http://www.fao.org/ag/agl/agll/wrb/wrbdocs.stm>.
- Fetzer, K.D., Enright, E., Grenzius, R., Kubiniok, J., Schwartz, C. & Morel, J.L. 1998. *Garden Soils in South-Western Germany (Saarland) and North-Eastern France (Lorraine)*. 16 World Soil Science Meeting, Montpellier, August 1998, France. CD congress.
- García-González, S. & Sánchez-Camazano, M. 1968. Differentiation of kaolinite from chlorite by treatment with dimethylsulphoxide. *Clay Minerals*, **7**, 446–451.
- Holmgren, G.G.S. 1967. A rapid citrate-dithionite extractable iron procedure. *Soil Science Society of America Proceedings*, **31**, 210–211.
- Ibn al-Jatib. 1998. *Historia de Los Reyes de la Alhambra*. Editorial El Legado Andalusi. Universidad de Granada, Granada.
- Kaufman, I.R. & James, B.R. 1991. Anthropogenic epipedons in oyster shell middens of Maryland. *Soil Science Society of America Journal*, **55**, 1191–1193.
- Kellogg, C.E. 1952. *Our Garden Soils*. The Macmillan Co. New York.
- Kübler, B. 1968. Evaluation quantitative du métamorphisme par la cristallinité de l'illite. *Bulletin Centre de Recherche Pau-SNPA*, **2**, 385–397.
- Lindsay, W.L. & Norvell, W.A. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, **42**, 421–428.
- Lupiani, E., Soria, J. & Pérez, A. 1985. *Mapa Geológico a Escala. 1: 50000 de Granada (Hoja Topográfica 1009)*. IGME (Instituto Geológico y Minero de España), Madrid.
- Martín-García, J.M., Delgado, G., Párraga, J.F., Bech, J. & Delgado, R. 1998. Mineral formation in micaceous Mediterranean Red soils of Sierra Nevada, Granada, Spain. *European Journal of Soil Science*, **49**, 253–268.
- Morel, J.L., Florentin, L. & Schwartz, C. 1999. Définition, diversité et fonctions des sols urbains. *Comptes Rendus de l'Académie d'Agriculture de France*, **85**, 141–152.
- Morel, J.L., Schwartz, C., Florentin, L. & de Kimpe, C. 2005. Urban soils. In: *Encyclopedia of Soils in the Environment* (ed. D. Hillel). Elsevier, Oxford.
- van Olphen, H. 1977. *Clay Colloid Chemistry*. John Wiley & Sons, New York.
- Pérez-Pujalte, A. & Prieto, P. 1980. *Mapas de Suelos y Vegetación de la Provincia de Granada (escala 1: 200000)*. Estación Experimental del Zaidín, CSIC, Granada, Spain.
- Rossiter, D.G. & Burghardt, W. 2003. *Classification of Urban and Industrial Soils in the World Reference Base for Soil Resources: Working Document*. At: <http://www.itc.nl/personal/rossiter>.
- Sandor, J.A. & Eash, N.S. 1995. Ancient agricultural soils in the Andes of Southern Peru. *Soil Science Society of America Journal*, **59**, 170–179.
- Schleuß, U., Wu, Q. & Blume, H.P. 1998. Variability of soils in urban and periurban areas in Northern Germany. *Catena*, **33**, 255–270.
- Schwertmann, U. & Taylor, R.M. 1989. Iron oxides. In: *Minerals in Soil Environments* (eds J.B. Dixon & S.B. Weed), pp. 379–438. Soil Science Society of America, Madison, WI.
- Sergeyev, Y.M., Grabowska-Olszewska, B., Osipov, V.I., Sokolov, V.N. & Kolomenski, Y.N. 1982. The classification of soil microstructures of clay soils. *Journal of Microscopy*, **120**, 237–260.
- Smart, P. 1979. Microstructure, manipulation. In: *Encyclopedia of Soil Science, Part 1* (eds R.W. Fairbridge & C.W. Finkl), pp. 300–306. Dowden, Hutchinson & Ross, Stroudsbridge, Pennsylvania.
- Soil Conservation Service. 1972. *Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples*. US Department of Agriculture, Washington, DC.
- Soil Survey Staff. 2003. *Keys to Soil Taxonomy*, 9th edn. United States Department of Agriculture/Natural Resources Conservation Service. At: http://soil.usda.gov/technical/classification/tax_keys.
- Velde, B., Goffé, B. & Hoellard, A. 2003. Evolution of clay minerals in a chronosequence of poldered sediments under the influence of a natural pasture development. *Clays and Clay Minerals*, **51**, 205–217.
- Vilchez, C. 1991. *El Generalife. Editorial Proyecto Sur*, Granada, Spain.
- Waltman, W.J., Cunningham, R.L. & Ciolkosz, E.J. 1990. Stratigraphy and parent material relationships of red substratum soils on the Allegheny Plateau. *Soil Science Society of America Journal*, **54**, 1049–1057.
- Yong, R.N. & Warkentin, B.P. 1975. *Soil Properties and Behaviour*. Elsevier, Amsterdam.
- Zhang, M., Ma, L., Li, W.Q., Chen, B.C. & Jia, J.W. 2003. Genetic characteristics and taxonomic classification of Fimic Anthrosols in China. *Geoderma*, **115**, 31–44.