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Unearthing anthropogenic and natural footprints: pedogenesis of a polyevent soil at *San Lorenzo ad Septimum Abbey* (Italy)

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Abstract
Polyevent soils represent ideal systems for investigating how the sequential combination of multiple natural and human processes and interruptions affects the development of a landscape. This investigation particularly focuses on deciphering the anthropogenic footprints embedded in the soil and tracing how human activities—from ancient settlements to modern interventions—have left indelible marks on pedogenic pathways. As a paradigmatic case study, a pedon surveyed in the present "Vegetable garden" built on the old green site of *San Lorenzo ad Septimum Abbey* (an important human settlement even before 3.9 ky BP) in Aversa city (Italy) was investigated. The research examined the possible predominance of pro-isotropic or pro-anisotropic pedogenetic trends using the following approach: (i) historical documentation, (ii) pedological and pedo-archeological survey, and (iii) the analysis of the distribution of physical-chemical parameters along the soil profile. The investigated pedon represents a paradigm of how polyevent soils could form. In fact, a combination of natural, dramatic incidents, as well as human interventions applied at different levels of consciousness and purpose, contributed to the formation of a polyevent sequence of buried horizons. Both natural and anthropic pro-anisotropic pedoturbations characterise such a sequence and enable the detection and elucidation of pedogenic trends strictly linked to human settlement and land use, thereby highlighting that man has acted as an incisive pedogenic factor since primeval times.

Keywords Buried soils, Historical archives, Anthropogenic pedoturbation, Soil-landscape interaction

1 Introduction

The original concept of "monogenetic" soil (MS) closely matched that of climatically equilibrated normal soil. According to Bryan and Albritton [4], a MS was one in which the soil continued to develop toward an endpoint in equilibrium with the present climate. Thus, climatic stability served as the basis and underlying tenet of monogenesis [29]. Monogenetic profiles were viewed as the result of pedogenic processes, described by a set of variables with specific relationships among themselves, over a period sufficient to allow soil attributes to form. Therefore, by definition, a "polygenetic" soil must have experienced at least two such episodes of monogenesis and has finally developed a complex assemblage of attributes in response to changes in the pedogenic variables. Thus, if it could be demonstrated that the climate—or some other external factor or variable—had changed, the soil could be considered polygenetic [45]. Beckmann [2] said it best when he opined that a soil has a heritage rather than an origin. However, Bryan and Albritton's polygenetic concept was notably restrictive in that a significant change, e.g., glacial-interglacial magnitude, was envisioned [63]. How should minor climatic oscillations be handled? Johnson and Watson-Stegner [28] and Johnson et al. [29] had an easy answer. Because pedogenic pathways are continually affected to varying degrees by changes in external and internal forcing, all soils should be considered polygenetic. Johnson and Watson-Stegner's [28] definition of the "polygenetic" concept lies at the other end of the continuum from Bryan and Albritton's [4], suggesting that very subtle and minor changes are sufficient to render a soil polygenetic. Thus, because all soils have indeed undergone even imperceptible process changes, they must all be polygenetic. In this vein, Johnson et al. [29] argued that polygenetic soil and polygenesis connote multiple genetic linkages among exogenous and endogenous processes, factors, and conditions, including evolved accessions, thresholds, and feedback loops that vary over time. From this point of view, all soils are polygenetic, and if all other things are equal, the older the soil, the more polygenetic it is [29]. Under this viewpoint, because pedogenic pathways have always been subtly shifting and evolving, the notion of the MS should be considered moot.

On the other hand, Schaetzl and Anderson [50] take the middle ground by affirming that polyevents (PS) have demonstrably undergone a significant environmental change, whether intrinsically or extrinsically driven. Many soils, especially the latest Holocene soils, might still be best thought of as monogenetic. If we discard the concept of monogenesis, then we must adopt another term for soils that have undergone subtle versus significant pathway changes [22]. There is a good reason to distinguish between the two soil types, and by regarding all soils as polygenetic, there is no way to communicate the distinction. Furthermore, under the Johnson and Watson-Stegner [28] definition, polygenetic soils need not exhibit measurable expression of their polygenesis. Birkeland [3] asserted, and Schaetzl and Anderson [50] agreed, that the pedogenic impacts that confirm polygenesis, i.e., the chemical and morphologic signatures within the profile, must be detectable; if they are not, then the polygenetic impact may be negligibly small. If polygenesis need not be physically or chemically expressed, the term loses its meaning because it cannot be scientifically verified.

This complexity necessitates a precise terminology that links pedogenesis directly to depositional history. Indeed, while polygenetic soil refers to the impact of multiple sequential processes [54], we used the term polyevent soil to specifically describe a pedon whose developmental trajectory has been repeatedly truncated, buried, and subsequently rejuvenated by discrete, chronologically constrained natural or anthropogenic events [26]. This framework enables the direct correlation between specific stratigraphical layers (paleosols, cultural strata, tephra) and the timing of human-landscape interaction.

In this context, polyevent soils (*vide infra*), especially those with clearly delineated buried horizons, act as invaluable stratigraphic archives, preserving imprints of successive environmental changes and anthropogenic interventions, much like layers in a historical manuscript. Understanding such complex soil genesis, particularly in the context of polygenetic and polyevent soils, is paramount for reconstructing past environments and human-landscape interactions, forming the very foundation of soils as archives [47].

The purpose of this study is to contribute to the study and interpretation of patent PS characterised by buried horizons formed under the pressure of specific natural and anthropogenic factors and processes, which drove the evolution and transformation, often sudden and dramatic, of soils that could be designated as polyevent soils. This work explicitly aligns with the "soils as archives" framework, providing a detailed case study of how sequential soil-forming processes can preserve a rich, layered history of both geological events and human interactions with the landscape.

As a paradigmatic case study, a pedon surveyed in the present "Vegetable garden" built in the old green site of *San Lorenzo ad Septimum* Abbey in Aversa city (Caserta Province, Campania region, Italy) was investigated. Such a site was an important human settlement, probably even before 3.9 ky BP [37]. The pedogenic features of the selected profile were investigated by detecting and interpreting the natural or anthropic pressures that determined and characterised soil evolution at small and large scales.

This integrated analytical design corresponds to a multiproxy approach *sensu* Holliday [26] and Retallack [47], widely employed in paleopedology and geoarchaeology to decouple and verify different lines of evidence when reconstructing environmental and anthropogenic soil formation processes. In this sense, the term refers to the combined use of stratigraphic, pedological, geochemical, and historical proxies to strengthen paleoenvironmental and cultural interpretations through independent datasets [23].

The research attempted to find evidence for the possible predominance of pro-isotropic or pro-anisotropic pedogenetic trends using the following multi-criteria approach: (i) historical documentation, (ii) a pedological and pedo-archeological survey, and (iii) analysis of the distribution of physical-chemical parameters along the soil profile.

2 Materials and methods

2.1 Study area

The pedon was surveyed at the *San Lorenzo ad Septimum* Abbey in the city of Aversa, which is located in the middle of the "Campanian Plain", a large graben formed by the subsidence of the crystalline carbonatic bed during the late Pleistocene along NW-SE fault lines, on which the Campanian volcanic district subsequently developed (Fig. 1a). Aversa city (Caserta Province) is the hub of the so-called "*Terra di Lavoro*", i.e., "Tillable Land" once known as "*Campania felix*" (fertile Campania), a large tract of arable land north of Napoli province. It is almost flat, averaging 40 m a.s.l. From a geologic viewpoint, pale lapillus and pyroclastites from Phlegraean Fields (Third Period) overlay the Neapolitan Yellow Tuff (NYT) in the study site (14.9 ± 0.40 ka BP; [18]) [51]. Incoherent facies of NYT, along with the typical stratified pyroclastites of distal facies, are found along the alignment *Alveo dei Camaldoli-Villa di Briano*, i.e., from Naples to Caserta [19]. Below the NYT, a coarse, matrix-less polygenetic breccia is found, likely originating from Ignimbrite Campana (28 ± 0.11 ka [17]) and other older materials.

To make appropriate historical comparisons, a more accurate chronology will be provided during the description of the investigated pedon. However, some information is briefly reported here. Historically speaking, the *San Lorenzo ad Septimum* Abbey was

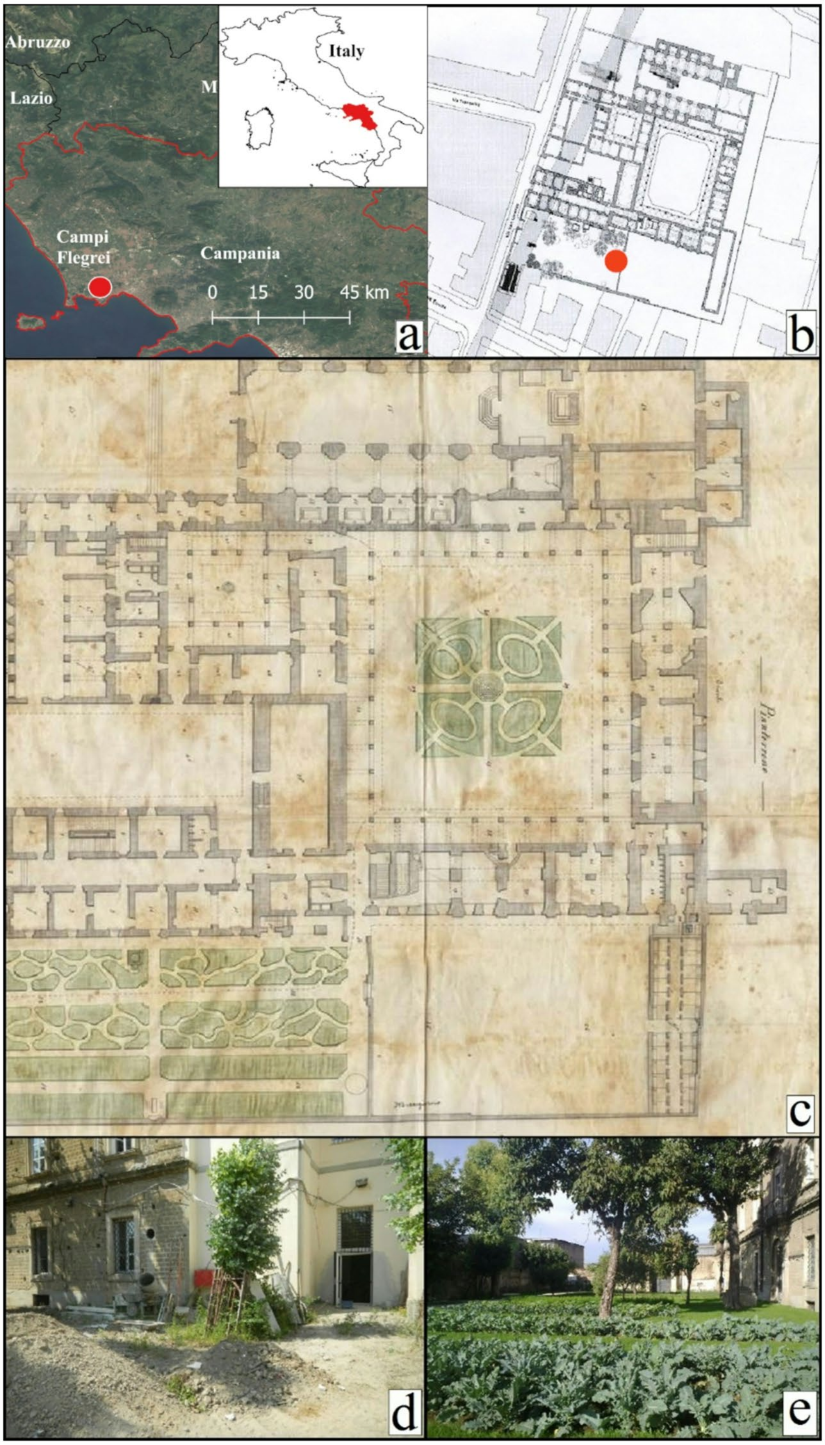

Fig. 1 Location (red dot) in the Campanian volcanic district (**a**), in the planimetry of the Insula of *San Lorenzo ad Septimum* (**b**), in the hold Abbey building (**c**), in the sampling site before (**d**) and after (**e**) pedotechnical intervention. The grey tape (**b**) shows the reconstruction of the road layout of the old Via Campana [37]. The circle (**a** and **b**) shows the localization of the sampling site. Technical plan (1878) of the old Abbey building (**c**), showing the "Artistic Mechanical Institute". On the bottom-left side (**c**), it is also evident that the location of the former *Abbott Garden*, whose legend designated it as the "Garden for Mr. Director's own use". Path walkways are evident within vegetation (possibly ornamental hedges)

built at the 7th mile (from which its epithet is derived) of the old *Via Campana* (Campanian Road), an important thoroughfare laid out in approximately the 4th century BC [37]. During Roman times, the study site was a government emplacement that gradually became the nucleus of a Christian community. In the 10th century, the Lombardic Princes built the first monastery, which became an important Abbey during the Norman kingdom in the 11th–12th centuries. Later, since 1776, the Abbey was enlarged alongside (Fig. 1b) the Via Campana [27], and the soil within the monastery was designed as the so-called *Abbott Garden* (Fig. 1c). Afterward, the site underwent a series of events; in 1807 the monastery was suppressed, afterwards becoming a college for young women (the *Casa Carolina*) which was replaced by various institutions and schools until 1970, when it was abandoned (Fig. 1d). In 1992, the old Abbey building was designated as the headquarters of the present Department of Architecture and in 2010, a pedotechnical intervention [6] restored the vegetable garden (Fig. 1e), just adjacent to the buried *Abbott Garden* (Fig. 1c).

2.2 Soil analysis

Representative samples were taken from the boundary to boundary of each soil horizon, with a minimum of 3 kg per horizon [56]. Unless otherwise specified, all samples were subjected to physical-chemical analyses performed on air-dried < 2 mm soil in accordance with the official procedures published by Ministero delle Politiche Agricole e Forestali [38].

The sand (2.0–0.02 mm), silt (0.02–0.002 mm), and clay (< 0.002 mm) fractions were separated by pipette and wet sieving following pre-treatment with H_2O_2 and sodium hexametaphosphate. Textural classes were identified according to USDA [56]. The soil pH was measured potentiometrically with a glass electrode in a soil/solution mixture at 1:2.5 (H_2O). The soil electrical conductivity (EC) was calculated on a 1:5 soil: water mixture. Organic carbon (OC) was determined according to the Walkley–Black oxidation method. Total N (Nk) was determined by means of the Kjeldahl procedure, and total P by the H_2SO_4 and H_2O_2 acid digestion method. Total carbonate was estimated by treatment with excess HCl and the volumetric determination of CO_2. Active carbonate was measured by treating the soil samples with 0.1 M ammonium oxalate for two hours, followed by the determination of unreacted oxalate by titration with 0.1 M $KMnO_4$. The cation exchange capacity (CEC) was measured by extraction with $BaCl_2$ + TEA at pH 8.2. The fractionation of soil inorganic P was determined with a method proposed by Kovar and Pierzynski (2009). According to a method proposed by Lowe [34] and Buondonno et al. [7], the following three primary soil phenolic matter (SPM) fractions were analyzed: (i) "total" (SPMt), (ii) "soluble" and/or "labile" (SPMs), and (iii) the fraction with a "high" (SPMh) affinity for the soil body. Other phenolic parameters [7], such as SPMt/TOM and SPMh/SPMs, were also calculated. Total organic carbon (TOC) was determined by mineralization with 2 N $K_2Cr_2O_7$ and 96% H_2SO_4 solutions at 160 °C for 10 min according to Springer and Klee [57].

All the previously reported physical-chemical parameters were analyzed in triplicate. Values in the text indicate the mean ± standard error of the mean.

3 Results and discussion

3.1 Soil classification

The pedon was described using standard soil survey methodology (Schoeneberger et al. 2012) and classified as loamy, concretic, mixed, calcareous, thermic Vitrandic Xerofluvent [55]. The single pedon classification together with the designation as a Fluvent at the Sub Order level has been applied rigorously following the principles and rules of the USDA Soil Taxonomy for soils developed in stratified, non-uniform parent material [55]. As a matter of fact, such rules imposed on us to consider the multiple buried units not as separate soils, but as relict or cumulic horizons within a single pedon that has experienced multiple episodic burial and subsequent rejuvenation, thus fully complying with the defining characteristic of polyevent soil [26, 47].

According to the IUSS Working Group WRB [65], the pedon studied can be interpreted within the Technosol-Anthrosol-Andosol intergrade domain typical of soils formed on tephric and anthropogenic parent materials. The upper horizons ($^\wedge A_b$; 2–4 $^\wedge A_b$) consist of human-altered and human-transported (HAHT) materials, including brick and cement fragments, conferring the *Technic* Qualifier, while the presence of relict anthropogenic organic enrichment ($5A_{pb}$) with high P, N, and OC contents functions as an *Anthric* horizon following WRB 2022 definitions (IUSS Working Group WRB, 2022).

The underlying layers ($5B_b$ to $7C_{k_2}$) contain abundant volcanic glass, lapilli, and pumice fragments, showing initial vitric and andic properties and are weakly weathered; these justify the *Vitrandic* reference to Soil Taxonomy and, under WRB, satisfy the criteria for *Andic* material at depth. Taken together, the profile is best described as a Cumulic Vitric Technosol (Anthric, Andic).

The term *Cumulic* reflects the pedosedimentary accumulation of multiple buried horizons within 2 m, each produced by discrete depositional and anthropogenic episodes; *Vitric* refers to the substantial content of volcanic glass shards; *Technosol* designates the surface and subsurface horizons dominantly composed of technogenic substrates; and the secondary qualifiers *Anthric* and *Andic* denote the organic-enriched, horticulturally modified layers and the incipient andic properties derived from tephric material. Such classification effectively conveys both the genetic processes and anthropogenic overprinting that define the *San Lorenzo* sequence, providing a more genesis-oriented framework than the Soil Taxonomy Fluventic grouping.

3.2 Soil morphology, main cycles, and morphogenetic differentiation

Tables 1 and 2 contain some of the investigated morphological, physical, and chemical features characterizing the *San Lorenzo* pedon. Due to the complex and thoroughly articulated site history, as will be explained in more detail later, the profile investigated was characterised by an impressive horizonation (Table 1).

From a morphogenetic viewpoint (Table 1), the *San Lorenzo* pedon can be subdivided into three primary formative cycles. Such a subdivision can be realized by the simultaneous consideration of all of the following fundamental aspects: (i) the historical and environmental documentation found for the area in public library and in old historic archives, (ii) a deep pedological and pedo-archeological survey aimed not only at exploring the morphological features of the pedon (in terms of soil horizonation) and the historic provenience of several artefacts found along the profile but also their significance in a well-known and previously investigated historical and environmental context and (iii) the analysis of the distribution of selected physical-chemical parameters along the soil profile. Additionally, and extremely important to understand the rationale under the proposed cycles, the site of *San Lorenzo ad Septimum* has been thoroughly investigated by different archaeological campaigns that have explored both the inner and outer areas of the *San Lorenzo* Church and a part of the area that presently hosts the Department of Architecture [37]. Different dating methods, both classical (i.e., characterized by the identification of specific, well-recognized artifacts) and modern scientific methodologies (such as radiocarbon dating), were used during these investigations to precisely date the various discoveries [37].

3.2.1 Third cycle

The III and last Cycle (Tables 1 and 2) starts from the field surface and extends to a depth of – 40 cm b.f.l. (below field level), with an horizonation of ^A_{upk1}, ^A_{upk2}, ^A_{upk3}, 2^C_u/A_b, 3^A_{ukb}, 4^CB_{ub}/A_b; the “caret” symbol (^), used as a prefix, indicates the horizons formed from human-transported materials (HTM), while the lowercase letter “u” identifies horizons containing artefacts [55].

All the reported lithological discontinuities are associated with relevant color variations (Table 1), such as very dark brown to brown (7.5YR2/3-10YR4/3) in ^A_{upk}1, 2, 3, pale yellow (2.5Y8/2) in 2^C_u/A_b, dark brown (7.5YR3/3) in 3A_{ub}, and again pale yellow (2.5Y8/2) in 4^CB_{ub}/A_b. Additionally, as usually recorded in these pedogenetic conditions, such discontinuities are clearly also marked by variations in the rock fragment (RF) content, as well as by the total and active $CaCO_3$ concentration (Table 2).

Overall, this Cycle III encompasses the so-called “contemporary” horizons, all clearly anthropogenic, beginning in 2010 (from the first surface horizon ^A_{upk1} representing a consequence of the latest pedotechnical interventions) and ending in 1807 (until to 4^CB_{ub}/A_b), when the monasteries ended their activities [6]. These horizons represent clear anthropogenic footprints, showcasing how successive human activities, including pedotechnical interventions and informal landfills, have drastically altered the original soil morphology and composition.

In particular, in 1807, the monastery was suppressed by anticlerical laws during the regime of Napoleon Bonaparte, the acting King of Italy. In 1810, the facilities of the former monastery were converted into the so-called “*Casa Carolina*”, a college devoted to the education of aristocratic girls until 1814 [40], which was later replaced in the ensuing years by various institutions and schools that usually offered artistic or technical courses of study. For example, a plan drawn by the Land Office of Caserta (Fig. 1c) it is evident that the historical Abbey building hosted an “Artistic Mechanic Institute” in 1878; in 1970 [40] the use of the building as a teaching centre ceased and it was abandoned (2^C_u/A_b, 3^A_{ukb}, 4^CB_{ub}/A_b); some areas were also subjected to illegal landfills [37]. From this viewpoint, even if no official documentation existed regarding the type of materials that were thrown into the landfill (due to their illegal nature), evidence from artefacts (e.g., brick fragments, earthy materials, limestone gravel and plastic probably originating from cement bags) found along the profile during the pedological investigation, as well as the evident presence of so-called human-altered and human-transported (HAHT) material [55], characterised by an enhanced chaotic horizonation (2^C_u/A_b, 3^A_{ukb}, 4^CB_{ub}/A_b), strongly suggests that the main contribution arose from building activities and practices.

Table 1 Selected morphological properties of the pedon studied

Horizon	Depth (cm)	BD[a]	Color (moist)	Structure[b]	Consistence[c]	Pores[d]	Roots[e]	Concentrations[f]	Permeability[g]
^A_{upk1}	0–5	A, S	7.5YR2/3	1, vf, gr	vfr	3 co	3, m/f, V	CAC, m, 1, O, C, VFR	RA
^A_{upk2}	5–10	A, S	10YR 4/3	1, vf, gr	vfr	3 co	3, m/f, V	CAC, m, 1, O, C, VFR	RA
^A_{upk3}	10–15/20	A, S	10YR 3/3	1, vf, gr	vfr	3 co	3, m/f, V	CAC, m, 1, O, C, VFR	RA
2^C_u/A_b	15/20–25/30	C, S	2.5Y 8/2 (C horizon) 10YR 5/3 (A horizon)	0 (C horizon) 1, vf, gr (A horizon)	vfi (C horizon) vfr (A horizon)	3 m/co	1, f, V	FDC	RA
3^A_{ukb}	25/30–32/35	C, S	7.5YR 3/3	1, f, gr		2 f	1, f, V	CAC, f, 1, O, C, VFR	RA
4^CB_{ub}/A_b	32/35–38/39	A, S	2.5Y 8/2 (CB horizon) 7.5YR 3/3 (A horizon)	0 (CB horizon) 1, vf, gr (A horizon)	fi (CB horizon) vfr (A horizon)	3 m/co	1, f, V	FDC	RA
5A_{pb}	38/39–49/51	C, S	10YR 2/3	2 vf gr	vfr	2/3 m/co	2, m, V	FDC	M
5B_{b1}	49/51–65/68	C, S	10YR 3/4	1, f, gr	vfr	2 vf/f	–	FDC	M
5B_{b2}	65/68–85/90	C, S	10YR 4/4	1, f, gr	vfr	1 vf	–	FDC	M
5C_u/B_{kb1}	85/90–100	C, S	2.5YR 3/3	1, f, gr	vfr	1 f	–	CAC, c, 2, O, C, FR	M
5C_u/B_{kb2}	100–110	C, S	2.5YR 3/3	1, f, gr	vfr	1 f	–	CAC, c, 2, O, C, FR	M
5C_u/B_{kb3}	110–120	C, S	2.5YR 3/3	1, f, gr	vfr	1 f	–	CAC, c, 2, O, C, FR	M
5B'_b	120–130	C, S	10YR 4/3	1, f, gr	vfr	1 vf	–	–	M
6C_k	130–140	C, S	2.5YR 5/3	3, f, gr	vfi	1 f	–	CAC, m, 2, O, C, FR	M
7 C	140–155	C, S	10YR 3/3	2, f, gr	fr	1 f	–	–	M

Table 1 (continued)

Horizon	Depth (cm)	BD[a]	Color (moist)	Structure[b]	Consistence[c]	Pores[d]	Roots[e]	Concentrations[f]	Permeability[g]
$7C_{k1}$	155–165	C, S	10YR 2/3	2, f, gr	fr	1 f	–	CAC, m, 2, O, D, VFR	MS
$7C_{k2}$	> 185	–	2.5YR 3/3	2, f, gr	fr	1 f	–	CAC, m, 2, O, C, FI	MS

a = Boundary

Distinctness: A = abrupt, C = clear; Topography: S = smooth

b: Grade: 0 = structureless, 1 = weak, 2 = moderate, 3 = strong; Size: vf = very fine, f = fine; Type: gr = granular

c: vfr = very friable, fr = friable, fi = firm, vfi = very firm

d: Quantity: 1 = few, 2 = common, 3 = many; Size: vf = very fine, f = fine, m = medium, co = coarse

e: Quantity: 1 = few, 2 = common, 3 = many; Size:, f = fine, m = medium; Orientation: V = vertical, H = horizontal

f: Kind: FDC = finely disseminated carbonates, CAC = CaCO3 concretion; Quantity: f = few, c = common, m = many; Size: 1 = fine, 2 = medium; Shape: O = spherical; Boundary: C = clear, D = diffuse; Hardness: VFR = very friable, FR = friable, FI = Firm

g: MS = moderately slow, M = moderate, R = rapid

Table 2 Selected physical-chemical properties of the pedon studied

Horizon	Depth (cm)	RF[a] (%)	Texture			Class[b]	pH-H_2O	EC (dS m^{-1})	Total $CaCO_3$ (g kg^{-1})	Active $CaCO_3$ (g kg^{-1})
			Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})					
$^\wedge A_{upk1}$	0–5	15.2	425	525	50	sil	8.4 (0.04)	0.344 (0.01)	36 (1)	19 (1)
$^\wedge A_{upk2}$	5–10	33.9	454	485	61	sal	8.4 (0.01)	0.406 (0.01)	90 (4)	25 (1)
$^\wedge A_{upk3}$	10–15/20	36.8	521	426	53	sal	8.6 (0.02)	0.406 (0.02)	237 (4)	61 (3)
$2^\wedge C_u/A_b$	15/20–25/30	73.1	661	266	73	sal	8.9 (0.02)	0.269 (0.01)	776 (12)	82 (2)
$3^\wedge A_{ukb}$	25/30–32/35	55.7	582	366	52	sal	8.7 (0.00)	0.388 (0.01)	200 (2)	47 (1)
$4^\wedge CB_{ub}/A_b$	32/35–38/39	71.4	613	318	69	sal	8.9 (0.03)	0.496 (0.05)	544 (15)	57 (3)
$5A_{pb}$	38/39–49/51	20	529	430	41	sal	8.5 (0.00)	0.437 (0.03)	97 (0)	23 (1)
$5B_{b1}$	49/51–65/68	20.8	501	438	61	sal	8.6 (0.01)	0.392 (0.02)	57 (6)	28 (0)
$5B_{b2}$	65/68–85/90	23.7	397	529	74	sil	8.5 (0.05)	0.272 (0.01)	19 (0)	16 (0)
$5C_u/B_{kb1}$	85/90–100	23.2	423	496	81	l	8.2 (0.01)	0.320 (0.02)	14 (0)	14 (1)
$5C_u/B_{kb2}$	100–110	13.1	399	555	46	sil	8.2 (0.03)	0.304 (0.01)	14 (0)	13 (0)
$5C_u/B_{kb3}$	110–120	32.9	463	490	47	sal	8.2 (0.02)	0.285 (0.00)	15 (0)	13 (0)
$5B'_b$	120–130	28.0	320	618	62	sil	8.1 (0.01)	0.318 (0.01)	15 (0)	15 (1)
$6C_k$	130–140	20.7	353	584	63	sil	8.1 (0.05)	0.342 (0.02)	14 (0)	14 (0)
7 C	140–155	14.1	441	509	50	sil	8.0 (0.02)	0.378 (0.02)	17 (1)	16 (0)
$7C_{k1}$	155–165	5.5	402	532	66	sil	7.8 (0.01)	0.452 (0.02)	14 (0)	14 (0)
$7C_{k2}$	> 185	19.4	475	479	46	sal	7.5 (0.01)	0.521 (0.02)	18 (1)	13 (0)

Mean value ± (std. er.)

a = Rock fragments

b: sil = silt loam, sal = sandy loam, l = loam

On the other hand, the $4^\wedge CB_{ub}/A_b$ combination horizon reveals a perturbation resulting from the mixing of a strongly altered limestone gravel (component CB_{ub}) intercalated with small masses of soil (component A_b). Such gravel material is likely a residual of the loose screed used as a covering, in accordance with the late-baroque garden style of the walkways of the old *Abbott Garden*. Notably, in the 1878 technical plan (Fig. 1c), the former *Abbott Garden*, with still evident walkways, was designated as the "Garden for Mr. Director's own use", i.e., again exclusive to the site authority in force at the time [6].

In 1992, more than 20 years after its abandonment, the old Abbey building was finally restored and designated as the present Department of Architecture's headquarters. In 2010, as fully reported by Buondonno et al. [6], the area of the old *Abbott Garden* (see the II Cycle) benefited from an intensive pedotechnical intervention ($^\wedge A_{upk1}$, $^\wedge A_{upk2}$, $^\wedge A_{upk3}$) to restore the physical-chemical soil fertility thus becoming a decorative/vegetable garden again, a function for which it was much better-suited (Fig. 1e). From a taxonomic viewpoint, all of the III Cycle horizons are man-made composed of HTM or more precisely, HAHT material, either of natural (earthy materials) or artefactual origin (brick fragments, limestone gravel, and plastics). Overall, this part of the pedon clearly represents a soil that can reasonably be called anthropogenic [10].

3.2.2 Second cycle

The II Cycle horizons lie between −40 and −130 cm b.f.l., as 5A$_{pb}$, 5B$_{b1}$, 5B$_{b2}$, 5C$_{u}$/B$_{kb1}$, 5C$_{u}$/B$_{kb2}$, 5C$_{u}$/B$_{kb3}$, and 5B'$_{b}$ (Tables 1 and 2). The 5A$_{pb}$ likely is the old true surface horizon of the *Abbott Garden*, which exhibited that agronomic/aesthetical function from 1777 to 1807 [27]. Indeed, during that period, the Abbey was enlarged. The original "natural" soils, initially located outside of the old building, were incorporated into the new structure, thus officially becoming the substratum of the *Abbott Garden*, alongside (Fig. 1b), even if unconsciously, the famous Via Campana [27] whose original track was misplaced at least five centuries before [27, 37]. Indeed, this principal road, running from *Puteoli* (the present Pozzuoli) to the old *Capua* (the present Santa Maria Capua Vetere, which was one of the most important cities of the ancient world), was laid down by the Romans approximately during the 4th century BC and used, even if with decreasing frequency, till the 12th–13th century [37]. It was discovered in the investigated site (Fig. 1b) as late as 1986–1988 [37].

The hypothesis that the 5A$_{pb}$ horizon represents the old surface horizon of the *Abbott Garden* can be supported by an interpretation of the patterns of several physical-chemical parameters along the soil profile, with particular emphasis on those that might serve as markers for detecting buried A horizons. Buried horizons indeed represent a good marker for identifying anthropogenic soil disturbances and related modifications [66]. In this context, the buried horizons seem to represent paleosols rather than unaltered cultural sediments. Indeed, each buried layer exhibits pedogenic traits, such as a granular to sub-angular blocky structure, horizon-specific porosity, and organic-enriched matrices, indicating active soil-forming processes that were prior to burial [47]. For instance, when considering the 5A$_{pb}$, 5B$_{b_1}$, and 5B$_{b_2}$ horizons' features, they exhibit (Tables 1 and 2) (i) OC, N, and P marked increases (compared to their parent materials), along with (ii) distinct boundary development and root porosity, witness of sustained cultivation, humification, and bioturbation prior to burial. Such features align with the diagnostic criteria for cumulic or relict A and B horizons within anthropogenic soil sequences [16, 26]. Beneath these horizons lie relatively unweathered tephric and fluvio-volcanic materials acting as parent substrates. Such a vertical transition, i.e., from developed soil to less altered depositional layers, seems to be a clue that each buried horizon corresponds to a truncated paleosol, formed under episodic stability, before renewed sedimentation or construction. Thus, their designation as buried paleosols within a polyevent framework is both pedologically and stratigraphically based.

To simultaneously make the comparison more precise and easier, the experimental data were standardised (Figs. 2 and 3) to allow the management of adimensional data, whose distribution and variation along the soil profile are emphasised on a similar scale. Therefore, all of those parameters that specifically peak can be identified almost immediately as reliable markers—either positively or negatively—that correspond to the A horizons, with special reference to the *Abbott Garden* 5A$_{pb}$. Not all the investigated physical-chemical parameters have been reported graphically to avoid redundancy, as

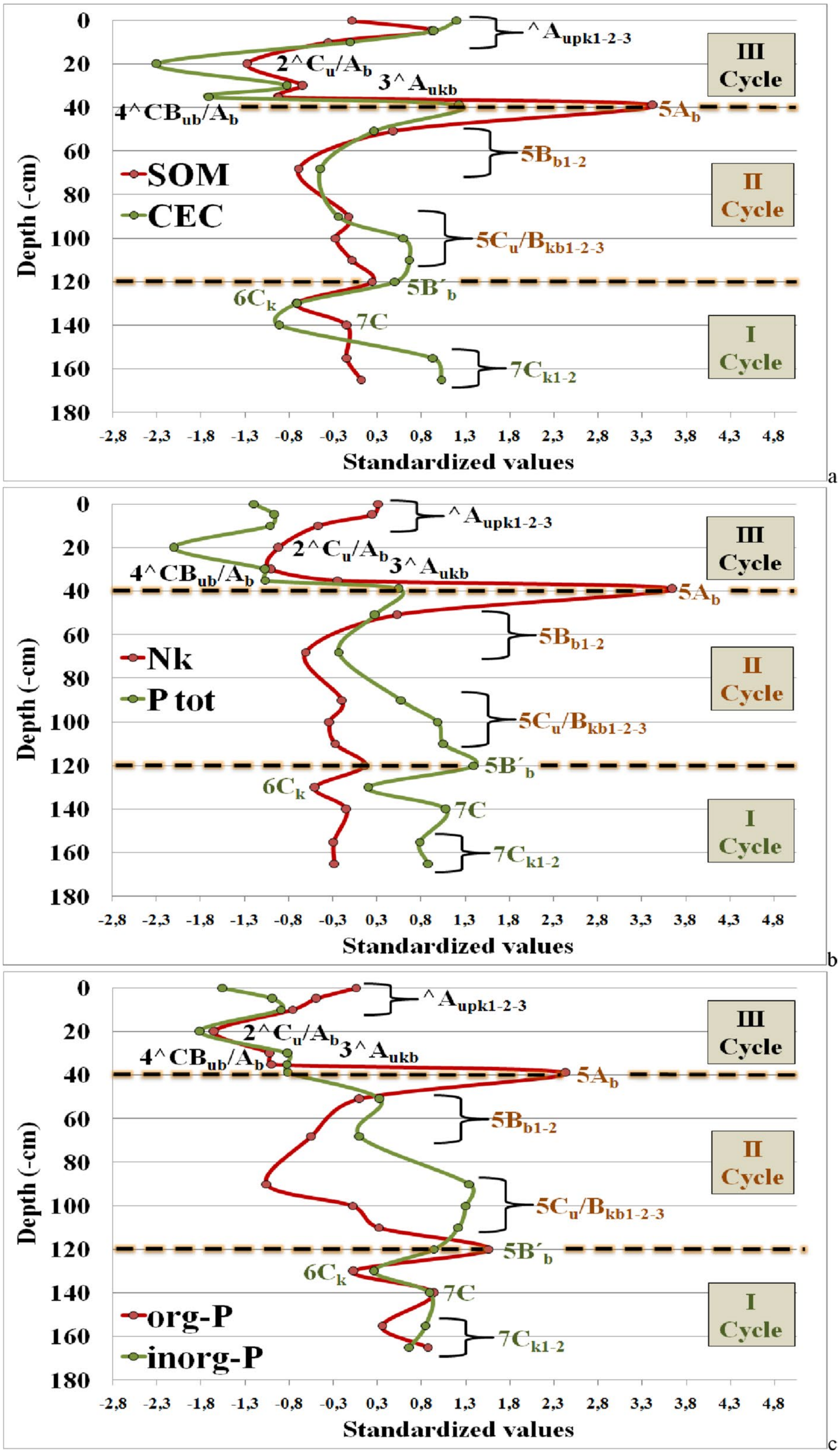

Fig. 2 Selected chemical properties along the soil profile

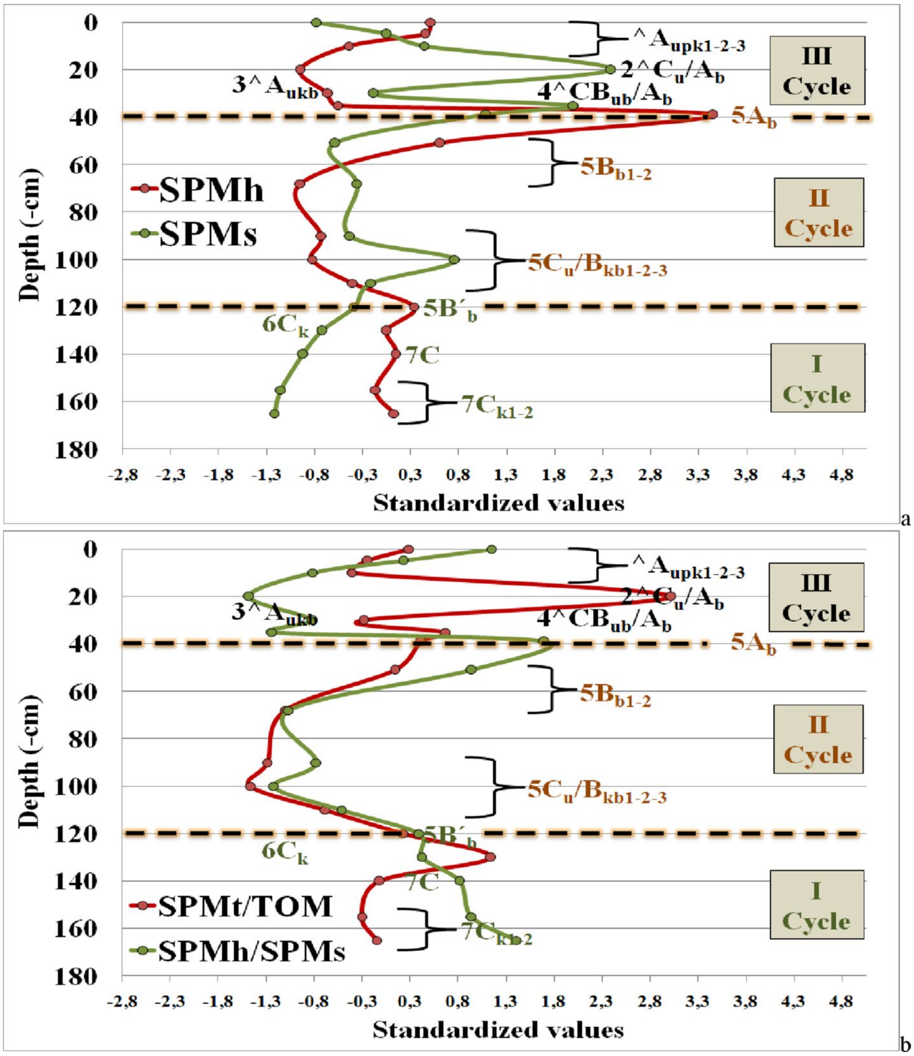

Fig. 3 Selected soil phenolic parameters along the soil profile

many of them show behaviour analogous to other previously determined parameters along the soil profile.

A comparative analysis of the graphs (Figs. 2 and 3) clearly shows that SOM (Fig. 2a), CEC (Fig. 2a), all of the humification parameters (not visualized since really similar to the SOM behaviour along the soil profile), Nk (Fig. 2b), org-P (Fig. 2c), and, probably best of all, phenolic parameters (Fig. 3) are all reliable markers for identifying the buried A horizons. All these parameters are clearly related to the SOM and, overall, are good indicators of soil fertility. The recorded variations in these parameters corresponding to the buried horizon 5A$_{pb}$ are all strongly consistent with the presence of an old natural surface horizon that was subjected to relatively intensive cultivation and fertilization. Indeed, the values recorded for the SOM (30.8 ± 1.3 g kg^{-1}), N (1.264 ± 0.000 g kg^{-1}), P (2.39 ± 0.01 g kg^{-1}), and K (3.0 ± 0.1 g kg^{-1}) in the buried 5A$_{pb}$ horizon are much higher than those generally observed in the soils in the area [9, 13]. Such values are indeed consistent with the presence of an old, cultivated surface horizon such as that which characterized the old Abbott Garden. At the time, the principal soil fertilizer was manure, which was historically used to fertilize that type of garden soil (Kellog [30]). From this viewpoint, the humification parameters (not reported) are all consistent with the presence of well-humified organic matter such as that typically found in animal manure [1].

Overall, the high levels of SOM, N, P, and K in the buried 5Apb horizon are not merely chemical anomalies but represent a pedogenic response to sustained cultivation and fertilization within the historical *Abbott Garden*, illustrating a distinct phase of anthropogenically-influenced soil genesis.

The deeper horizon 5B'b (– 120 to – 130 cm b.f.l.) was laid down after the so-called "*Pomici di Avellino*," a cindery/pumices Vesuvium eruption of 3.9 ky BP [58] that will be better explained later (First Cycle). In the horizons from – 50 to – 90 cm b.f.l. (5Bb1 and 5Bb2), clastic tuff and pumice materials were found, but earthenware and bricks fragments were collected as well (Fig. 4). The morphological features, historical-archaeological evidence, and common knowledge suggest that such artefacts likely date back to the Roman age, when—as reported by Jacazzi [27]—the study-site was a "*statio*" (i.e., a place from which lower-ranking detached-service soldiers performed temporary guard or police duties) or a "*mansio*" (a place at which official government travellers,

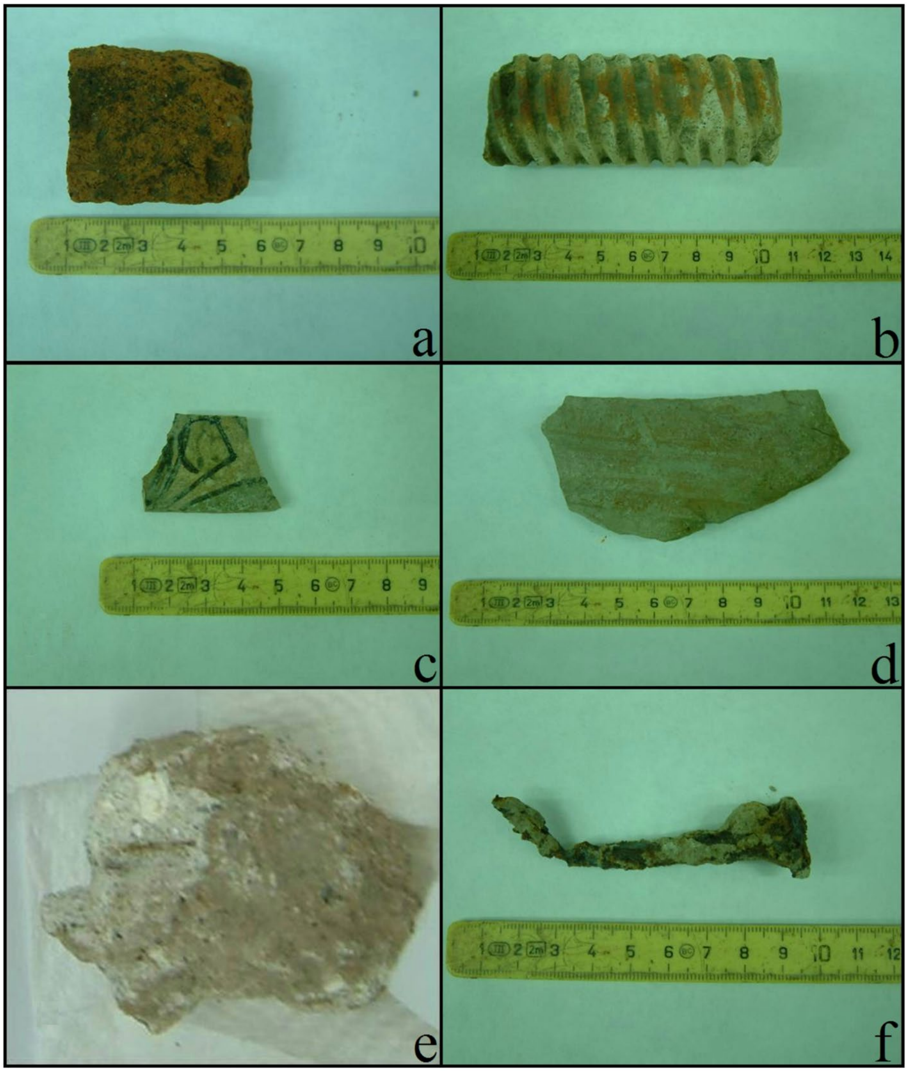

Fig. 4 Some examples of artefacts founded in the *San Lorenzo ad Septimum* pedon: II Cycle – "Middle". **a** = a brick fragment; **b** = earthen pipe; **c** and **d** = earthenware fragments; **e** = trace of mortar lime; **f** = a nail

including couriers, could sleep, change horses, and bathe). For instance, a brick fragment (Fig. 4a) appears to have been produced using the typical Roman technique of *lateres crudi*, i.e., by merely drying a red or whitish clay slurry in the sun and air [59]. Earthen pipes (Fig. 4b) were used to convey water during the reign of Augustus (14–14 BC), as explained by Vitruvius in his famous treatise *De Architectura* (29–23 BC). Such material was considered more wholesome than lead [67], pipelines of which were judged dangerous for humans due to the formation of the so-called *white lead* (PbCO3), a problem so great during the Roman period that a hypothesis by Nriagu [39] proposes that lead poisoning contributed to the decline of the Roman Empire. The earthenware fragments (Fig. 4c, d) are too small for a precise characterization. However, their shape and manufacture seem to be attributable to amphorae or greyware, two of the most common types of Roman pottery found at the site and dated to the Augustan period [37]. Traces of mortar lime (Fig. 4e) are consistent with the presence of the previously mentioned brick fragments. Finally, the evidence shown in Fig. 4f is the most common type of a Roman-made iron nail [20], characterized by a square-sectioned shaft and a flat head [12, 35]. The presence of Roman-era artifacts, such as *lateres crudi* bricks, earthen pipes, and iron nails, within the 5Bb1 and 5Bb2 horizons not only provides chronological markers but also pedo-archaeological evidence of anthropogenic disturbance and material deposition, influencing the soil's physical and chemical properties observed today. However, although archaeological artefacts provide valuable relative markers for identifying past human activities, their stratigraphic context must always be interpreted with caution. Historical sources and classical records cited for chronological support cannot be considered direct evidence, as their spatial and stratigraphic correlations may only be approximate [23, 47]. Post-depositional processes, such as soil reworking, fluvial disturbance, and anthropogenic mixing, can alter the original position of these materials [16, 26]. This is the reason why, to reduce these uncertainties, chronological inferences have always been linked to changes in soil morphological and physical-chemical trends (variations in OC, N, $CaCO_3$ content, etc.; Tables 1 and 2) too. This multidisciplinary approach ensures that the temporal correlations discussed here remain grounded primarily in the observed pedological evidence. In fact, all these observations within these horizons suggest "anthropogenic footprints," probably illustrating the intense human occupation and construction activities that shaped the soil's composition and structure during that period, thus enriching the soil's archival narrative.

The material composition of Roman-era artifacts themselves could have had a lasting influence on the soil's physical-chemical properties. Brick fragments and mortar residues of that time, typically rich in calcium carbonate and silica, gradually released soluble Ca^{2+} and other cations, probably contributing to the high carbonate concentrations and moderately alkaline pH still observable in the 5Bb horizons [53]. Likewise, the inclusion of iron nails and other metallic fragments introduced dispersed Fe oxides and hydroxides during oxidation, locally enhancing reddish hues (2.5YR 3/3) and influencing the distribution patterns of free Fe detectable today [14]. Earthenware pipes and ceramics, often containing illite and kaolinite, could act as minor sources of aluminosilicates and influence micro-aggregation and textural stability by releasing fine clay particles through weathering [8]. Additionally, over centuries, the progressive weathering of these anthropogenic inclusions would have led to pedochemical modification, such as an increased CEC and enhanced buffering capacity within the investigated horizons [33, 64]. Overall, Roman construction debris not only serves as a chronological marker but also could have acted as an active geochemical component that directly shaped the current pedophysical and morphological features of the soil [31].

The anthropogenic modification of soil structure observed in the 5Bb$_2$ horizon should be related to the multiple combined results of (i) compaction processes, (ii) textural mixing, (iii) the introduction of external materials, and (iv) maintenance practices. Recurrent trampling, construction-associated levelling, and the deposition of coarse, angular fragments from bricks, mortars, and lateritic floors increased bulk density, reduced macroporosity, and induced a more massive, platy structure; all features typical of mechanically compacted cultural layers [41]. Moreover, lime mortars and calcareous debris contributed to localized cementation and aggregate stabilization, preserving the fine granular to sub-angular blocky structure still visible under 5Bb$_2$ [31]. Indeed, although 5Bb$_1$ and the overlying transitional horizons share similar textures, the pedofabric in 5Bb$_2$ shows markedly denser packing and lower permeability, reflecting anthropostratigraphic hardening rather than natural illuviation or sedimentary compaction [23]. Courty et al. [16] argued that such anthropogenic impacts generate a characteristic horizon morphology defined by (i) reduced bioturbation, (ii) oriented voids, and (iii) partially compacted pedoplasmation. Consequently, the 5Bb$_2$ structure could be interpreted as a "residual imprint" of the Roman occupation, whose physical integrity has persisted through burial processes, distinguishing it in both morphological and genetic terms from both the younger anthropogenic horizons and the more pedogenically uniform above and below, respectively.

After the Roman period, the study site progressively became the nucleus of a Christian community [27]. During the Medieval period (i.e., the 10th century), the *San Lorenzo ad Septimum* Abbey was finally erected [37].

3.2.3 First cycle

The oldest, deepest I Cycle horizons (Tables 1 and 2) are found from − 130 to − 185 cm b.f.l., as the poorly pedogenised 6C$_k$, 7 C, 7C$_{k1}$ and 7C$_{k2}$ horizons. The 6Ck layer is a lens of poorly altered volcanic sand and cinders, predominantly reddish brown (2.5YR5/3), with scoriae and carbonate concretions, together with earthenware fragments. These morphological characteristics supported the hypothesis that it could represent a deposit linked to the so-called "*Pomici di Avellino*" eruption. Indeed, according to Sulpizio et al. [58], this deposit found in the Aversa area was generated during the final phase of that eruption and consists mainly of pyroclastic flow deposits and, to a lesser extent, fallout material. Furthermore, its presence has been detected in the Aversa plain at depths of 90–120 cm [62]. The "*Pomici di Avellino*" represents, along with those responsible for the destruction of Pompeii (79 y BC), the results of one of the most important Plinian-type eruptions in the Somma-Vesuvius volcanic district [52]. The name arose from the prevailing direction (towards Avellino, a Campanian city located to the east) of the falling volcanic materials (covering an area of approximately 2000 km^2). The Avellino eruption has been recently dated by Sevink et al. [52], using a new series of robust ^{14}C dates which yielded an age of 3945 ± 10 cal BP (radiocarbon ages are reported as calibrated years before present (cal BP), thus representing a precise time marker for the Early Bronze Age in Central Italy.

The underlying horizons (7 C, $7C_{k1}$, and $7C_{k2}$) are the typical residuals of the ancient floods of the *Volturno* and *Clanio* rivers, coloured dark brown (10YR3/3) to dark reddish brown (2.5YR3/3). Indeed, flooding events in the area still significantly affect soil evolution in various ways, including the fluvial regime, land geomorphology, and distance from the river channel [9, 13].

The classification of these basal horizons as fluvial is supported by both morphological and physical-chemical evidence (Tables 1 and 2). Their stratified texture, alternating fine and coarse silt layers, and the high sand + silt content exceeding 85% indicate deposition by low-energy alluvial and overbank processes typical of the *Volturno-Clanio* system [13]. Moreover, the presence of rounded lithoclasts and fine stratiform lamination, together with the moderately slow permeability and friable consistence observed in the $6C_k$ and 7 C horizons, seems to confirm a depositional rather than colluvial origin. Chemically, the elevated carbonate content (total $CaCO_3 > 15\%$, active $CaCO_3$ 10–18%) and the near-neutral to slightly alkaline pH (7.5-8.0) are compatible with typical fluvial deposits derived from the carbonate-rich pyroclastic and sedimentary catchments of the Campanian Plain [9, 13]. Within these horizons, some weak pedogenic features (incipient mottling, dispersed carbonate coatings, and minor Fe-Mn concentrations) suggest short-lived soil processes associated with temporary surface stability between flooding events, followed by re-burial [47]. This evidence suggests that these horizons represent genuine fluvio-volcanic deposits undergoing early pedogenic transformation, rather than purely sterile sedimentary layers.

The Cycle I, was characterized by a weakly developed soil structure (fine granular, friable), thus reflecting limited bioturbation and rapid burial after the Avellino eruption and subsequent fluvial inputs [50]. This weak pedogenic expression is best exemplified by the $6C_k$ horizon, where fine granular aggregates are interspersed with dispersed carbonate concretions and oxidized tephric particles, indicating incipient soil formation under conditions of partial drainage and rapid burial [21, 47]. The low porosity together with the moderately slow permeability recorded in the deeper C_k horizons indicate restricted drainage, favoring carbonate accumulation and incomplete leaching [47]. Carbonate concentrations were present as disseminated $CaCO_3$ and small concretions, thus marking episodic groundwater oscillations and secondary calcification, which are common in buried volcanogenic paleosols [21]. All these features collectively confirm that the genesis of the Cycle I layers resulted from a combination of sedimentary deposition, limited soil formation, hydromorphism, and early diagenetic carbonate production.

The evidence from both morphological and chemical parameters supports the volcanic origin of these deeper horizons. The presence of vitric ash and pumice lapilli fragments, together with the dominant silt + fine-sand texture and elevated active $CaCO_3$ values reported in Table 2, are consistent with tephric parent materials derived from the Avellino Plinian eruption [17, 58, 62]. Moreover, the slightly enhanced Fe_2O_3 content and reddish hues (2.5 YR 5/3–3/3) observed in $6C_k$ and $7C_k$ horizons reveal incipient oxidation of mafic glass shards; a typical process of initial weathering in volcanic materials [49]. At the same time, pH values around 8.0 and the presence of weak granular structure indicates the early stage of andic transformation. However, not yet the full development of an Andosol *sensu* WRB (2022), suggesting that these are tephric paleosols in a youthful weathering phase [11]. Together, these features confirm pedogenic alteration within a volcanic substrate rather than mere sedimentary accumulation. The data also suggest that after deposition, the volcanic tephra was rapidly covered by alluvial inputs from the *Volturno-Clanio* system, producing the observed weak development; a scenario implying limited exposure time between eruption and burial [13, 52].

Finally, the substratum at the study site (below the $7C_{k2}$ horizon, not shown in the figures) is characterized by pale lapillus and pyroclastites from the Phlegraean Fields (Third Period), overlying the NYT. The NYT is the product of the largest known trachytic phreatoplinian eruption, and its overall weighted mean age (assessed by 40Ar/39Ar dating method) is 14.9 ± 0.4 ka [18].

3.3 Pedogenic processes and soil genesis

From a pedogenic perspective, the superimposed horizons forming the *San Lorenzo* sequence exhibit a combination of pedogenic processes typical of cumulic, relict, and anthropogenically modified soils of volcanic origin in the Campanian Plain.

The soil genesis interpretation was based on the measured physical-chemical parameters, as well as the morphological features (Tables 1 and 2). Among the other investigated aspects (for example, the artifact presence), observed variations (such as pH: 7.5–8.9; $CaCO_3$: 10–80 g kg^{-1}; OC: 0.3–30 g kg^{-1}; texture, etc.) throughout the whole soil profile reveal the alternation of depositional events and, consequently, different pedogenetic processes. In the $5A_{pb}$ horizon, high C, N, P, and phenolic matter values coincide with granular structure and friable consistence, confirming humification, enhanced bioturbation, and anthropogenic enrichment through cultivation and manuring [1]. In contrast, the subsurface $5B_b$ units show lower SOM but marked carbonate mottling and moderate BD, indicative of partial decalcification and re-cementation through percolating Ca-rich solutions. Additionally, the underlying $6C_k$-$7C_k$ horizons exhibit a weak structure together with dispersed concretions, reflecting early diagenetic carbonate precipitation and hydromorphism related to fluctuating water tables [47]. Overall, the whole vertical distribution of these parameters reveals repeated phases of profile rejuvenation following burial events, thus confirming that the observed soil pattern derives from multiple pedogenic trajectories rather than a single continuous formation process.

The deepest units ($6Ck$-$7Ck_2$), derived from tephric and fluvio-volcanic deposits, show early andic alteration with incipient allophane formation and secondary carbonate precipitation, reflecting initial vitric weathering and decalcification under fluctuating hydromorphism [47].

The overlying buried $5A_{pb}$-$5B_b$ horizons display enhanced OC, N, P, and K contents, consistent with humification and bioturbation related to horticultural use and anthropogenic enrichment by manuring [1, 30]. Textural, morphological, and chemical heterogeneities across $5B$-$5C_u/B_{kb}$ horizons also suggest illuviation-deposition cycles where colloidal material and fine ash were translocated during periods of surface stabilization and then buried by cultural or alluvial inputs [42, 43]. In contrast, the uppermost anthropogenic horizons ($^\wedge A_b$; 2–4 $^\wedge A_b$) are dominated by anthroturbation and technogenic aggregation, forming human-altered and human-transported (HAHT) materials *sensu* Soil Survey Staff [55].

Altogether, these alternations of natural and anthropogenic pedoturbations, coupled with episodic burial and rejuvenation, define the polyevent pedogenesis of the *San Lorenzo* profile, where each stratigraphic level records a discrete combination of pedogenic processes within successive stable and depositional phases [26, 50, 60].

In addition to anthropogenic disturbances, several natural pedoturbations have been recognized throughout the investigated profile, such as: (i) faunal activity; (ii) root bioturbation; and (iii) periodic fluvial reworking, all evident in the deeper and intermediate horizons. Indeed, the disrupted microaggregation, root traces, and irregular subtle boundaries (observed in the $6C_k$ and $7C_k$ horizons) are indicative of soil fauna pedoturbation and root penetration [61]. Additionally, the observed complex interbedding and lamination (some C_k and CB horizons) appear to clearly reflect processes such as episodic flooding and (subsequent) sediment redeposition by the *Volturno* and *Clanio* rivers, all key agents of natural pedoturbation in the Campanian Plain [13, 21]. Such natural processes have operated in tandem with anthropogenic impacts, contributing to the intricate mosaic of mixed-origin horizons and strongly influencing the polyevent character of the profile.

The prevailing pedogenic trends in the *San Lorenzo* sequence are distinctly pro-anisotropic. This is evidenced by (i) the heterogeneous horizonation, (ii) compositional discontinuities, and (iii) abrupt lithological/structural transitions at every cycle and subcycle, thus indicating repeated interruptions of soil-forming processes [3, 50]. Additionally, each burial, pedoturbation, or anthropogenic event generated new boundaries and reset pedogenic trajectories across both vertical and lateral dimensions; all features contrasting with pro-isotropic soils where pedogenesis advances uniformly through time and space [25, 28]. The combination of cultural sediment inputs, fluvial deposits, and volcanic tephra contributed to marked anisotropy, which the polyevent framework can resolve chronologically. Thus, pro-anisotropic genesis not only prevails in this context but is the essential outcome of polyevent soil evolution in landscapes subject to repeated natural and human disturbance.

4 Final re-reading of the profile and reasons for the polyevent concept

Our comprehensive interpretation of the *San Lorenzo ad Septimum* soil profile reveals it as a multifaceted pedological and archaeological archive, where each horizon encapsulates distinct chapters of environmental and human history.

An interpretation of the processes by which the horizons were formed, based on previously observed properties and historical events, can be placed in a broader chronological and cultural context for the landscape and environment. This comprehensive interpretation solidifies the *San Lorenzo* pedon's standing as a "soil archive," offering a sort of lens through which to examine millennia of intertwined soil genesis and anthropogenic footprints on the Campanian landscape. In particular, from bottom to top, the following cycles and sub-cycles can be highlighted (Fig. 5):

- I Cycle "Ancient" encompasses: I.1: ≤ 14.9±0.4 ky "Neapolitan Yellow Tuff" BP to ≈3.9 ky BP "*Pomici di Avellino*", as "*Volturno*/*Clanio* Rivers floods"; and I.2: ≈ 3.9 ky BP "*Pomici di Avellino*";
- II Cycle "Middle" encompasses: II.1: ≤ 3.9 ky BP "*Pomici di Avellino*" to <400 BC "Via Campana", as "From *Via Campana* to Roman Culture"; and II.2: < 400 BC "*Via Campana*" to <1777 "*Abbot Garden*", as "Transition and Medieval Period" (the extremes of such a period are fuzzy); and II.3<1777 to 1807 "running *Abbot Garden*";
- III Cycle "Contemporary" encompasses: III.1: > 1807 to 1992 "XIX to XX century"; and III.2: 1992 to 2010 "Present".

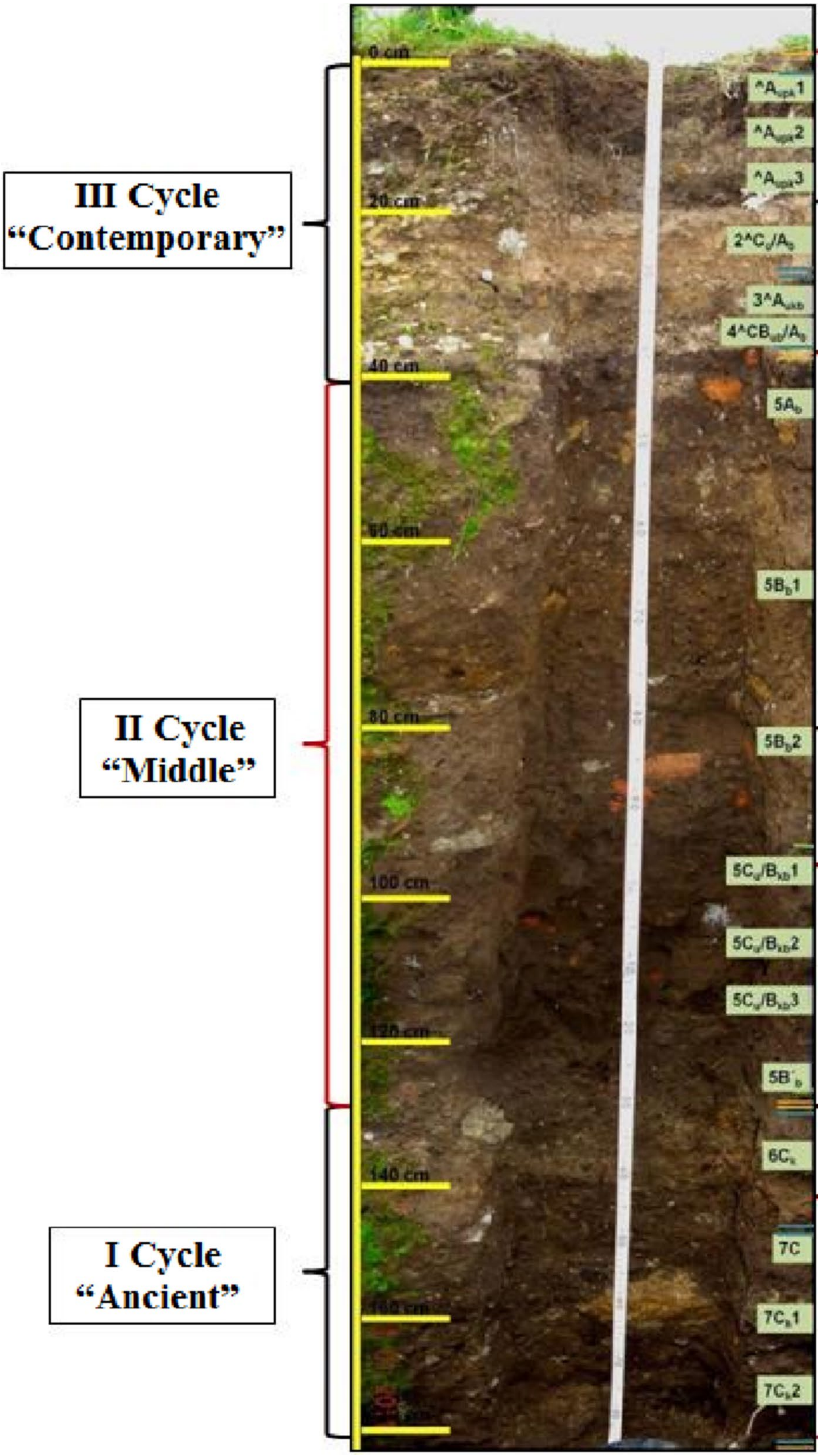

Fig. 5 *San Lorenzo ad Septimum* pedon with the three main cycles

Such a horizonation, characterized by several lithological discontinuities and buried horizons, reflects a polyevent, strongly pro-anisotropic soil genesis as a consequence of (i) various site uses and (ii) several natural or anthropogenic burial events. Indeed, the San Lorenzo profile should be both polycyclic, i.e., produced by more than one cycle of weathering, and polygenetic, i.e., subjected to a wide variation in one of its principal formative factors [11]. Such an observation, related to a peculiar pedon characterized by both polycyclic and polygenetic processes and phenomena, fits well with the concept of polyevent soil. Indeed, as reported in this study, the integration of historical and environmental information with field and laboratory morphological, physical-chemical, and property data led us to interpret, set, and subdivide the horizonation of the *San Lorenzo* pedon into three primary formative cycles.

The *San Lorenzo* pedon is an example of polyevent soils. Actually, a combination of natural, dramatic incidents and human interventions, applied with varying levels of consciousness and purpose, contributed to the formation of a polyevent sequence of buried horizons. This is characterized by both natural and anthropic pro-anisotropic pedoturbations, allowing the detection and elucidation of pedogenic trends strictly linked to human settlement and land use, thus highlighting that humans have acted as an incisive pedogenic factor in primeval times. Indeed, this study has shown how such polyevent soils serve as possible natural archives, capturing the complex interplay between geological forces and human endeavors, thereby providing a possible foundation for understanding long-term environmental and cultural landscape evolution.

In summary, the *San Lorenzo* sequence is best understood as a single polyevent, a cumulic soil rather than as a set of discrete, independent soils. The entire profile forms a continuous control section in which water, roots, and solutes can move vertically, and several diagnostic features (carbonate redistribution, weak redox mottling, faint bioturbation, and organic-carbon gradients) clearly integrate signals from multiple stratigraphic units. At the same time, the presence of sharp contacts, anthropogenic sealing layers, and coarse, carbonate-rich or construction-derived materials locally buffers downward transmission of later processes, so that some buried horizons preserve their original fabric with only limited overprinting. This combination of vertical connectivity and stratigraphic selectivity is precisely what defines polyevent and cumulic soils in the sense of classical pedogenic models, in which a single soil individual records multiple, temporally distinct phases of surface formation, burial, and rejuvenation within a single functional pedon.

5 Conclusions

This study demonstrates that the *San Lorenzo ad Septimum* soil is not merely a complex sequence of buried horizons but a verifiable polyevent soil, in which distinct natural and anthropogenic processes can be individually recognized and correlated with specific historical phases. By integrating pedological and archaeological data, the research formally establishes anthro-pedogenesis as a quantifiable factor in soil evolution for the Campanian region. The results confirm that pro-anisotropic trajectories prevail in soil systems repeatedly exposed to deposition, reworking, and cultural modification, expanding the concept of soils as archives beyond descriptive archaeology to a reproducible analytical framework. Consequently, this pedon serves as a reference model for understanding how human and natural mechanisms interact to control soil development in long-inhabited volcanic landscapes. Due to the inherent complexities of reading a poly-event soil, our work is affected by some limitations. Focusing intensely on a single pedon naturally restricts the spatial scope. The investigated profile is just one piece of a much larger and complex area with its related human and environmental history; thus, gaps or ambiguities can leave interpretive windows open, making a definitive, absolute dating for every nuanced layer a continued challenge. Looking ahead, to truly broaden our understanding, future research should expand to encompass a wider array of pedons within the *Abbey* grounds and perhaps even adjacent areas. Incorporating even more advanced, high-resolution analytical techniques could unveil finer details of pedogenic processes and material provenance. Ultimately, fostering even deeper interdisciplinary collaborations would enrich our collective ability to reconstruct these dynamic landscapes.

Author contributions

Conceptualization: E.G. and G.F.C.; Data curation: E.G. and A.G.; Formal analysis: E.G., A.G., A.A., and G.F.C.; Investigation: E.G. and G.F.C.; Methodology: E.G., A.G., A.A., and G.F.C.; Software: A.G. and G.F.C.; Supervision: E.G.; Validation: E.G., A.G., A.A., and G.F.C.; Visualization: E.G., A.G., and G.F.C.; Roles/Writing - original draft: E.G., A.G., A.A., and G.F.C.; Writing - review & editing: E.G., A.G., A.A., and G.F.C.

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Data availability

All raw data can be provided by the corresponding author upon request.

Declarations

Ethic approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare no competing interests.

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