AMAZONIAN DARK EARTHS, GEOARCHAEOLOGY OF

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Introduction

Amazonian Dark Earths (hereinafter ADEs) are expanses of anthropogenic soils that formed on generally nutrient-poor upland soils of the Amazon basin during pre-Columbian times. Expanses of ADEs range from <1-80 ha and overall agricultural aptitude is higher than the vast majority of soils in the region. These soils are much sought after by local farmers who use them to grow specific crops. Most of the documented expanses of ADEs are found on Tertiary sediments located in riparian and interfluvial positions of the Amazon basin. However, instances are also reported on Quaternary alluvial sediments and on human-made earthworks, highlighting that the formation of these soils was an outcome of specific forms of pre-Columbian settlement. The discovery of ADEs alongside the main waterways of the region has been a crucial rubicon for Amazonian archaeology: ADEs record the effects of pre-Columbian indigenous societies' creative manipulation of environmental affordances and thus highlight that human inhabitation of the Amazon basin was, and is, much more than efficient adaptation to environmental limitations. Examined from a strictly archaeological perspective, ADEs are one of the best archaeological signatures of sedentary occupations that can be ascertained in a region with limited archaeological preservation potential. Their ubiquity provides strong evidence for the existence of more sedentary and demographically-denser indigenous societies in the Amazon basin before European colonisation. ADEs are *sui generis* archaeological artefacts of extraordinary relevance for present-day concerns: soil scientists are currently studying the properties and formation of ADEs in order to develop techniques of soil amelioration that permit recuperation and amendment of degraded and infertile soils.

Definition

ADEs collectively refer to circumscribed expanses of organically-enriched mineral soils found mostly within the non-flooding terrain of the Amazon basin. Expanses of these soils vary in size, shape and location: linear expanses have been reported as patches extending over hundreds to thousands of metres along *terra firme* bluffs that overlook the major waterways of the basin. However, smaller patches, either oval in shape or draping the horizontal surface of the landform on which they are located, also exist on relict floodplain locations, on *terra firme* areas adjacent to alluvial lakes and flooding forest, on *terra firme* interfluvial terrain away from large rivers, and on alluvial sediments. Moreover, soil horizons with similar characteristics are reported on both shell middens and artificially-constructed pre-Columbian mounds built on flooding landscapes of the Amazon basin and beyond.

The topsoil of ADEs (the A horizon) is generally darker (grey, brown, or ink black in colour) and deeper (not infrequently reaching down to 60 cm), standing in sharp contrast with the thin A horizons of regional soils.

Studies distinguish between *terras pretas*, i.e. pottery-rich black soils with a deep A horizon, and *terras mulatas*, larger surrounding or adjacent expanses of darkened soils whose surface horizon lacks archaeological artefacts but whose nutrient status is intermediate between *terras pretas* and the broader soilscape (Sombroek 1966). Most scholars consider this contrast to reflect a distinction between sedentary pre-Columbian settlements and associated outfields. The vast majority of studies of ADEs concentrate on settlement-related *terras pretas*. These studies demonstrate that compared to the underlying B horizon or comparable adjacent soils, the A horizon of ADEs shows a higher cation exchange capacity, a more basic pH, and higher concentrations of, among others, organic carbon, calcium, phosphorus, manganese, potassium, barium, copper, manganese, strontium, and zinc. Estimates of black carbon contents using molecular markers, such as benzenepolycarboxylic acids, suggest that the organic horizon of settlement-related ADEs (*terras pretas*) occlude up to 70 times more pyrogenic carbon (charred plant matter, i.e. charcoal) than adjacent Oxisols. This observation has been marshalled to suggest that high black carbon concentrations are key to the high organic matter retention of these soils (see Glaser & Birk 2011 for a recent review).

Historical Background

Amazonian Dark Earths were first described in 19th century Brazil as 'Terra Preta de Índio' (Indian's Black Earth) or simply as 'Terras pretas' (Black Earths), the reference to 'Indians' being a reflection of the fact that abundant pottery shards of evident pre-Columbian age could be seen on the surface. An anthropic origin for ADEs was advocated in these first descriptions: pioneering geologists like Smith and Hartt unhesitatingly related cultivated ADE patches along the lower reaches of the Amazon river to villages of former indigenous peoples (Myers et al. 2003). The results of the first soil chemistry analyses conducted on ADEs allowed Katzer (1903) to argue that their high fertility was the result of unusual concentrations of charcoal and decomposed organics in the fine earth fraction, properties which he argued had also made them attractive to farmers in the past. As early as the 1920s, ethnologist and archaeologist Nimuendajú (see Neves 2004) noted that their geographical distribution and associated archaeological remains (including artefacts, earthworks, and roads) suggested they had originated in densely-populated, sedentary pre-Columbian settlements. For the first part of the 20th century, however, these opinions remained isolated. Nimuendajú's archaeological research went unpublished and, more significantly, was beyond the intellectual web of earth scientists until the mid 1960s. The size of farmed expanses in the Brazilian Amazon, the fact that many local farmers did not recognise their human-made origin, a lack of clear-cut evidence for their contemporary formation, and the scant attention accorded to them by important Amazonian archaeologists (see below), led some researchers to advocate a variety of 'geogenic' models about the origin of ADEs. In broad outline these models argued that ADEs are patches of fertile soils that formed from localised, non-anthropogenic accumulations of organic and/or mineral materials of fossil, volcanic or peaty origin. However, Klinge (1962) argued that high total and soluble phosphoric acid concentrations of ADEs evidenced an anthropogenic origin. In parallel, Hibert (1968) whose archaeological research documented the co-occurrence of dark earths and ceramic archaeological remains along the main rivers of the western half of the Brazilian Amazon, observed that ADEs formed on different types of Oxisols (Red and Yellow Latosols in the Brazilian soil classification). Like Nimuendajú, he suggested that ADEs resulted from long-lived settlement. However, it was undoubtedly soil scientist Wim Sombroek's (1966) interpretation of the physico-chemical characteristics measured in settlement-related ADEs located on the Belterra plateau (near Santarém, Brazil), that convincingly refuted geogenic models for their origin. Sombroek pointed out that the overall topography and drainage of the plateau were incompatible with suggestions that organic material had accumulated in small water bodies. He next noted that instead of the random distribution which would be expected from a natural phenomenon, the landscape position of ADE expanses suggested deliberate selection of areas suitable for the invigilation of navigable waterways. He then reported particle-size and x-ray diffraction data that evidenced the same overall texture and kaolinitic parent material in *terras pretas* and neighbouring soils, effectively overruling a source in volcanic debris. Finally, he enunciated the distinction between *terras pretas* and *terras mulatas*, i.e. between settlement-related anthrosols and settlements-peripheral anthrososls, and presented distributional evidence that expanses of the former were often associated with much larger surrounding or adjacent areas of the latter. It is fair to say that Sombroek settled the matter of anthropogenic *vis-à-vis* geogenic origins in the 1960s.

Although Sombroek's work inaugurated the modern era of studies of ADEs, discussions of Amazonian pre-Columbian history did not initially take stock of their presence or ultimate significance. This lack of attention was not trivial in the face of contrasting understandings of pre-Columbian societies advanced by leading scholars of the day: Betty Meggers (1971) militantly disregarded suggestions that Amazonian upland soils could be made fertile and thus envisioned a low ceiling for sedentism and demographic growth based on the retroduction of ethnographically-observed slash-and-burn agriculture. Donald Lathrap (1970) placed his weight behind the suggestion that the crop base of large pre-Columbian populations would have relied on intensive cultivation of rich alluvial sediments. While some argued that the agricultural aptitude of upland soils was not *per se* low nor necessarily unchanging (Carneiro 1983), this lack of attention to Sombroek's findings all but blinded archaeologists to the possibility of creative manipulation of environmental affordances in the past until the 1980s (Herrera et al. 1980-1, Eden et al. 1984, Andrade 1986, Mora 1991), when pioneering pedo-archaeological investigations in the Colombian Amazon highlighted the part that ADEs could have played in permitting denser populations in pre-Columbian times. However, Sombroek's research was a crucial intellectual referent for the first systematic survey of ADEs in the Brazilian Amazon, led by geographer Nigel Smith(1980), who presciently surmised that the dark colour of these soils was a result of the deposition of comminuted charcoal. Recognition of their ubiquity, in turn, permitted links with studies of Amazonian resource management - specifically practices resulting in deliberate environmental alteration (Posey 1984) and/or the presence of biotic legacies in the landscape (Balée 1989) – and prompted a reassessment of geographers' arguments about pre-Columbian settlement patterns and population density (Denevan 1992; Denevan 1996). It is accurate to say that since the late 1980s and 1990s, ADEs have become an increasingly more important component of archaeological arguments about pre-Columbian Amazonia (Heckenberger et al. 1999; Petersen et al. 2001; Arroyo-Kalin 2010a).

Key Issues

The make-up of ADEs

Many of the concentrations of edible or useful fruit trees marshalled by Balée (1989) as evidence of anthropogenic disturbance grow on expanses of ADEs (see alsoJunqueira et al. 2011).Some researchers have considered ADEs as remains of pre-Columbian house gardens produced by the deliberate composting of settlement residues (Andrade 1986; Myers 2004), others perceive them as an outcome of the accumulation, perhaps also management, of waste associated with settlements (see review in Erickson 2003; Schmidt 2013, in press), yet others postulate alluvial inputs to make these soils more productive (Herrera et al. 1992, Woods, 1995), and still others emphasise the role that pottery production may have play in understanding their makeup (Lima et al. 2002; Schaefer et al. 2004; Sergio et al. 2006). It is evident that these opinions do not necessarily exclude each other, especially because a single, Amazon basin-wide account of these soils' formation processes is unlikely to exist. This explains in part the appeal of the 'kitchen midden' model (Sombroek et al. 2002), which suggests that a combination between the decomposition of excrements, household garbage, bone, and organic constructions and the concentration of ash and charcoal derived from ground-level fires, are the most important inputs resulting in the formation of settlement-related ADEs. A rise in soil pH associated with organic waste is argued to permit the formation of resistant organo-mineral complexes and thus augment the retention of a more stable pool of organic matter (Sombroek 1966); larger quantities of pyrogenic carbon are considered to provide more ubiquitous sorption sites for metals; a combination of illuviation and faunal mixing of comminuted and/or decomposed constituents is considered to homogenise these inputs and contribute to the dark colour of these soils (Vacher et al. 1998; Kern et al. 2004; Topoliantz & Ponge 2005); both organic and inorganic inclusions are thought to become metabolised by soil microbes and stabilized through humification (Glaser & Birk 2011).

Micromorphological studies have been crucial to ascertain some of these processes as well as the ubiquitous presence of microscopic charcoal, bone, and pottery fragments in ADEs. Soil micromorphological methods were initially deployed by soil scientists (Lima et al. 2002; Schaefer et al. 2004) to compare *terras pretas* and nearby Oxisols. This study permitted linking the aforementioned anthropogenic inclusions and enhanced elemental concentrations. A geoarchaeological study using soil micromorphology (Arroyo-Kalin 2008b; Arroyo-Kalin et al. 2008; Arroyo-Kalin 2010a; Arroyo-Kalin 2012) has expanded these results significantly. By comparing ADEs from within archaeological sites and contrasting observations between clayey- and sandy-textured ADEs from different archaeological sites, it has shown that high levels of nutrient enhacement co-vary with the presence of microscopic inclusions (especially charcoal and bone), highlighted that high densities of microscopic pottery fragments and baked clay are reflected in high magnetic susceptibility values for these sediments, and presented empirical evidence to distinguish between settlement-related *terras pretas* and settlement-peripheral *terras mulatas*. *Terras mulatas* have been found to contain a significant volume of microscopic charcoal (lower than *terras pretas*) but, despite high nutrient status, only negligible fragments of microscopic bone, pottery, or burnt clay. Magnetic enhancement of *terras mulatas* has been interpreted as evidence of microscopic charcoal that did not originate *ex situ* but is the result of repeated near-surface burning associated with past management. Coupled with micromorphological observations suggesting scraping, raking, and/or churning of the soil, this research has provided important support for Denevan's (2004) suggestion that *terras mulatas* are the result of spatially-concentrated, fire-intensive cultivation practices in pre-Columbian times. It has also helped to emphasise that settlement-related ADEs bear the material signatures of midden material, house floors, and other activity areas.

From a geoarchaeological perspective, important questions arise about the build-up of settlement-related ADEs, which are anthropogenic cumulic soils that in many cases lack a clear nearby source of sediments. Micromorphological analysis accords a role to bulking-up of the sand- and silt-sized fractions by large quantities of microscopic inclusions of anthropic origin, to mixing by soil fauna, and, indirectly, to ash deposition (Arroyo-Kalin et al. 2008). These observations shed light on two conceptual models for ADE horizonation: Vacher et al. (1998) suggest that vegetation clearance associated with the implantation of settlements would lead to destruction of organic litter, after which inhabitation-related production of organic and mineral inputs and the modification of mineral surfaces through trampling, soil removal and other activities, would lead to the formation of a modal O-A-B soil profile with clearly established eluvial and illuvial subhorizons. The upper subhorizon would be directly affected by settlement activities and the lower one would accumulate inputs from the settlement surface. Visible differences between these subhorizons would be obliterated as the lower subhorizon becomes saturated with pigmenting soil constituents, effectively resulting in melanisation. At site abandonment, a new mineral surface (A horizon) would be developed through upwards translocation of sediments by soil fauna, obliterating settlement-related sedimentary structures (e.g. compaction) and interring artefacts in the organically-enriched sediment matrix. Woods (1995), in contrast, highlights that the accumulation of organic and mineral material would tend to bury the original surface, resulting in rising of habitation surfaces as subsequent occupations takes place. Given a modal O-A-E-B soil profile, he argues that organic inputs would result in an enhancement of the activity of soil fauna as well as strong melanisation of the new A horizon, transforming the sediments of the original A-E-B sequence into a transitional AB horizon. Further sedimentation associated with continued habitation would tend to result in repetition of the same process, i.e. build-up at the surface and down mixing as a result of increased activity of soil fauna. Whilst Woods' model is particularly useful to explain the thick A horizons most commonly noticed by soils scientists, there are elements in both models that resonate with empirical observations: ADEs should not be understood exclusively as thick A horizons that have expanded downwards but as an outcome of the accumulation of settlement debris, the effects faunally-induced burrowing, mixing, and/or churning of soil material, of the upwards or 'conveyor' translocation of sediments from lower in the deposit, and of a higher overall deposition of organic matter (Arroyo-Kalin 2008b).

The making-off of ADEs

In his classic review of Amazonian pre-Columbian community patterns, Myers (1973) argued that the larger and more complex settlement layouts that could be derived from ethnographic and ethnohistorical sources – single-family house communities, multi-family rounded or circular houses, plaza-centred groups of houses (including cases of multiple malocas around a plaza), and linear groups of houses strung alongside rivers and lakes – were all characterised by scrupulous maintenance of the patios, plazas, or circular plazas within, behind or around which dwellings were located. These maintenance practices resulted in debris accumulating as secondary refuse in either linear middens behind rectilinear rows of houses or in ring-shaped middens around other types of settlements (from single and multi-family house-based settlements to plaza-centred groups of houses). Erickson's (2003) recent survey of the ADE formation literature re-examines Myers's (1973) classic survey and suggests that ADE expanses could result from a combination between specifically-shaped refuse accumulations, remobilisation of enriched soils once they have formed, and overlapping occupations characterised by different settlement layouts. These suggestions are borne out by the compounded results of different ethnographic studies in Amazonia: Deboer and Lathrap's (1979) ethnoarchaeological study of San Francisco de Yarinacocha, in the Peruvian Amazon, shows that secondary refuse resulting from constant sweeping and raking of household and plazas/patios should, under ideal conditions, accumulate in settlement-peripheral middens and (to judge from the settlement plan they present) specific activity areas such as food preparation and pottery firing areas (see also Siegel & Roe 1986). Zeidler (1983) describes a 3-year old Achuar dwelling as a thatch-roofed oval area of some 160 m^2 enclosed by walls formed by upstanding peach palm logs. He observes that the position of debris within the house reflects, first, gender-ordained, communal and personal activity areas and, second, maintenance of clean spaces through sweeping. However, he also notes that the periodicity of sweeping opens up opportunities for artefacts to become interred as a result of trampling, a process that is assisted by sedimentation of ash, charcoal, and burnt soil produced by and accumulated adjacent to combustion features. In the upper Xingú region, research along the southern periphery of the Amazon basin has highlighted circular plaza-centred villages surrounded by rings of dwellings as contexts for the formation of ADEs (Heckenberger 2005; Schmidt 2013, in press). Chemical and physical analyses of a ring-like string of elevated rubbish middens behind house structures, as well as house sediments and plaza sediments show the lowest values of pH, organic matter, phosphorus, calcium, potassium, manganese, magnesium, and sodium in the latter areas, intermediate values within abandoned houses, and high values within middens. Middens form distinctive patterns on the landscape consisting of linear mounds along backyard edges and trails. These are used for the cultivation of home garden crops but can also be levelled to place houses on them. Comparable data are presented by Hecht (2003) at the Kayapó settlement of Gorotire, which identifies different types of middens beyond plazas and houses and records comparatively higher concentrations of key elements as a result of planned waste mangement. Silva's (2003) study of an Asuriní village similarly shows how regular maintenance of public spaces produces large middens behind houses, some being deliberate pilings of large amounts of debris and others more incidental accumulations. In northwest Amazonia, early 20th century ethnographic descriptions show thatched-roofed longhouses enclosing spaces internally divided into communal areas used for meals and transit, compartments for nuclear families, and areas in which manioc processing takes place. Fireplaces of different kinds and purposes were frequently used in different parts of the longhouse, resulting in the production of charcoal and ash. Many accounts suggest that the interiors were swept regularly, sometimes accompanied by wetting of the otherwise dry floors (Koch-Grünberg 1995 (1909)). More recent observations (Arroyo-Kalin, field notes) suggest that floors of thatched roofed structures are characterised by build-up of sediment in which significant amounts of organic debris, ash and charcoal accumulate. Roofed precincts restrict the transportation of air-borne sediments permitting, among other things, the accumulation of soot particles on the underside of roof thatching (this is encouraged in new houses to increase water-proofing). A number of different researchers (Neves et al. 2003; Neves et al. 2004; WinklerPrins 2008) point to various forms of localised 'dooryard' burning of organic debris that could result in localised, within-settlement concentrations of charcoal and other debris. Other activity areas of potential interest for the formation of ADEs are smouldering fires under racks used for smoking fish and, perhaps most intriguingly, areas in which pottery tempered with *caraipé* (obtained by ashing the bark of Licania octandra, see Hartt) was produced. The *caraipé* link deserves more focused research given that it could permit linking ADE formation to particular ceramic techno-sylistic traditions. All in all, it is clear that a variety of contexts for the formation of ADE must be considered.

ADEs in space and time

An up to date map of the spatial distribution of reported expanses of ADEs is being developed as a Google Earth map (WinklerPrins & Aldrich 2010). The overall distribution suggests ADEs are ubiquitous in the Amazon basin but, on the whole, less frequent or underreported as one approaches the westernmost lowlands of the Amazon basin. In terms of occupations, the oldest reported ADEs are associated with c. 2500 BP pre-ceramic occupations of the Massangana phase, Jamari river, in the upper Madeira basin, Brazil (Miller 1992). However, the vast majority of occupations include ceramic remains and charcoal that date from around or after 0 AD and, in many instances, from around 500 AD. Most of these occupations peak around or after 1000 AD (Arroyo-Kalin 2008a; Moraes & Neves 2012). Some controversy has existed about the extent to which *terra preta* sites reflect continued inhabitation as opposed to overlapping short-lived occupations (Meggers 2001; DeBoer et al. 2001; Heckenberger et al. 2001; Neves et al. 2003; Neves et al. 2004; Neves & Petersen 2006). A comparison between the 14C dates of soil-embedded microscopic charcoal and macroscopic charcoal associated with archaeological remains shows that the pyrogenic carbon pool of *terras pretas* is coeval with the most intense human occupations inferred from archaeological evidence (Arroyo-Kalin 2012). At the Manduquinha site, a relatively small ADE expanse occupied over a period of approximately 300 years prior to European contact, horizontal variability in elemental concentrations of the A horizon is interpreted as evidence for areas of transit, middens, dwellings and shells heaps, effectively suggesting a relatively stable settlement layout persisted during occupation (Kern et al. 2004). Studies of multi-component sites (e.g. Heckenberger et al. 1999; Neves 2003; Mora 2003; Moraes 2006) support Woods' contention that ADEs are accreting deposits in which numerous occupations are recorded. Thick A horizons in ADE are generally associated to anthropogenic enrichment of multiple surfaces and subsequent mixing by soil fauna, sometimes appearing as sub-horizons to other earth scientists (Arroyo-Kalin 2008b). Evidently this suggests that many of the best known ADE exemplars are large sites with protracted and intensive occupation histories. However, less-evident, perhaps incipient anthropogenic horizons are found associated with occupations that reach back to the early to mid-Holocene (Arroyo-Kalin 2010a).

Future Directions

Whilst much recent literature has emphasised the unique Amazonian character of these soils (Lehmann et al. 2003; Glaser & Woods 2004), archaeological investigations show that similar anthropogenic modifications are found beyond the Amazon basin, for instance in the north of Colombia, in the Orinoco basin, in the Guianas, and in subtropical areas south of the Amazon basin proper. This has led some to propose the need to reconsider the distribution of anthropogenic dark soils of pre-Columbian origin within the broader geographical context of the Neotropics (Graham 2006). Even casual perusal of studies from further afield highlights that anthropogenic soils and sediments have been linked to a very broad variety of situations, i.e. underscores the need to examine dark earth formation processes with attention to historical regional specificities. Notwithstanding, the significant appeal of their study in the Amazon basin ultimately resides in a heritage of archaeological interpretations that regards the Amazon basin as hostile to population growth and sedentism. ADEs lays to rest this suggestion and effectively tackles down the received truth that soil fertility was an insurmountable limit for pre-Columbian populations.

Amazonian Dark Earths are prized to this day by farmers because they achieve higher yields of staple lowlands cultivars such as manioc, permit the growth of acid-intolerant crops such as maize, and concentrate a high diversity of edible/useful fruit trees. The overall spatial distribution of ADEs might suggest co-occurrence between these soils and regions where bitter manioc is cultivated (Arroyo-Kalin 2010a; Fraser et al. 2011). However, more intensive archaeological survey is required to ascertain broad patterns of regional distribution as well as to determine any significant temporal gradients in their formation. Detailed consideration of their variability and associated plant and animal fossil assemblages is called for to answer a number of archaeological research questions: Given the ubiquity of microscopic bone fragments and the fact that bone apatite is a source of P and Ca, can fertile ADEs be linked to the ability of past populations to tap into abundant faunal resources? If this is the case then new and interesting questions arise regarding the feedback mechanism between fishing, the main source of protein in Amazonia, and the development of fertile agricultural soils (Arroyo-Kalin 2010b). Further question can be asked: to what extent have we grasped the full variability of the ADE phenomenon? Here it is crucial to take into consideration the little that we know about the variability of intra-settlement and, especially, settlement-peripheral soils (*terras mulata*s), which can be expected to vary according to broad precipitation patterns (Arroyo-Kalin 2012). One might further ask, where some of the well-developed expanses that we see today recycled for crop cultivation in the pre-Columbian past? Did they play a role in permitting the cultivation of certain crops? Were they dump heaps for the domestication of autochthonous Amazonian lowland crops? What does the spatial patterning of known occurrences indicate in terms of pre-Columbian population density and livelihoods (Arroyo-Kalin 2010b; cf. McMichael et al. 2012)? To what extent did increased soil fertility in ADEs lead to specific locales becoming more contested by pre-Columbian populations (Arroyo-Kalin 2008a)? Such questions can only be answered through interdisciplinary research that includes archaeological perspectives: it is otherwise impossible to establish basic spatio-temporal parameters that permit examining ADEs as historical outcomes of multiple processes. In conclusion, it can be stated that ADEs provide a paradigmatic example of a trans-generational and cumulative transformation of the landscape - one with incidental *and* deliberate components - in an environment long regarded as impenetrable. Consequently, the study of ADEs ultimately angles on the increasingly more significant role that human niche construction – as a long-term process associated with cultivation, husbandry and sedentism – is set to play in archaeological thinking in coming decades.

Cross-References

→ Agrarian Landscapes, Environmental Archaeological Studies of
→ Anthropogenic Environments, Archaeology of
→ Chemical survey of archaeological sites
→ Geoarchaeology
→ Historical Ecology and Environmental Archaeology
→ Landscape Domestication and Archaeology
→ Magnetic Susceptibility of Soils and Sediments in Environmental Archaeology
→ People as Agents of Environmental Change
→ Preservation of Environmental Archaeological Evidence
→ Soil Micromorphology
→ Urban Dark Earth

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