

Interactive comment on “Origin, distribution, and characteristics of Archaeological Dark Earth soils – A review” by Michael O. Asare et al.

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Interactive comment on “Origin, distribution, and characteristics of Archaeological Dark Earth soils – A review” by Michael O. Asare et al. Anonymous Referee #1 Received and published: 29 October 2020 Please kindly note that was hard for the present Reviewer following if authors have fully answered to his questions. Additionally, for some of the previous required comments authors “simply” ignored it. Additionally, they decided to follow a strange way to respond to my general and specific questions, i.e, by simply using a discursive strategy. This is not a “conventional” way for a revised version of a major revision affected paper. So, for your convenience, and in order to avoid a rejection proposal of your paper, I warmly suggest authors using the following scheme: Comments X: report here one of my 31 comments, chronologically listed from 1 to 31

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GENERAL COMMENTS (GC) 1. GENERAL COMMENTS-GC1: The review aimed to investigate about the distribution, evolution, and properties of archaeological dark earth (ADE), by additionally, i) providing an overview of different types of ADEs and their distributions, ii) describing their physical-chemical properties, and iii) identifying main questions for the future development in terms of new research activities Response: We appreciate all comments raised below. We have tried to answer all of them in the manuscript. In this response we have provided the line numbers and their corresponding statements/sentences for clarity. 2. GC2: Along the entire paper authors extensively used words such as "seems", "probably", etc. I can understand caution, but I think that the lack of courage in presenting their own ideas make your paper less attractive and lacking in novelty. If you have done a review on a specific subject, you must also be able to give your own motivated and convinced opinion. Response: We have revised all statements concerning the use of "seems" and "probably". Please see below the corrected and previous versions of the manuscript; Line 57: Thus, ABEs can hardly develop in semi-arid and arid regions probably because of the high decomposition rate of accumulated organic matter. Response:

Please see Line 88: Thus, ABEs can hardly develop in semi-arid and arid regions because of the high decomposition rate of accumulated organic matter. Line 186-187: Therefore, Terra preta genesis can be explained by formation from midden areas and probably home garden agriculture as also practiced today Response: Please see Lines 222-223: Therefore, Terra preta genesis can be explained by formation from midden areas and home garden agriculture as also practiced today. 3. GC3: Paragraph 2 is a little bit boring. In its present form it is just a list of ABE present around the world. Authors contribution in terms of new ideas and novelty, totally missing. Yes, you are writing a review, but you must be brave enough to add your personal idea in the context of exposed items Response: We have thoroughly explained parts of the review as suggested. We have also explained this section by provided some ideas on the formation of ABEs around the world. SPECIFIC COMMENTS (SC) 4. SC1 - Abstract: there are no reference about which are main aims and scope of your review. Please add; Re-

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sponse: We have included the aim of the review in the abstract as recommended here. Please see Lines 51-53: The study aimed to provide a detailed overview of the variability, distributions, and characteristics of ABEs relating to their classifications as well as the physicochemical properties SC2 - Abstract: honestly is badly organized. Authors started talking about that ABE is a "layer" (?) of anthrosol (I think you mean that ABE can usually be classified as Anthrosols according to FAO-WRB), passing for its origin and development till to its concentration in macro- and micronutrients. I don't see any logic organization. I would suggest starting for the classical scheme: background, aims and scope, main outcomes and conclusions. Otherwise, it is hard to be easily following it. Response: We have reorganized the abstract by explicitly stating the background, aims and scope, outcomes and conclusions of the review. For example, the outcomes of the review revealed that archaeological black earths are characterized by slightly acidic to neutral soil reactions and a substantially enriched by C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, Rb, and Ba in comparison to surrounding control (Please see lines 58-60). 6. SC3: Acronyms and terms: please note that rather using "archaeological dark earth (ADE)" it should be better using "archaeological black earth (ABE)"; Response: We have changed all archaeological dark earth (ADE) to archaeological black earth (ABE) in the manuscript. 7. SC4: Acronyms and terms: please note that rather writing "Archaeological Black Earth (ABE)" it should be better using "archaeological black earth (ABE)". The capitalization of the first letter in acronyms explanation was an odd, indeed overwhelmed, conception; Response: We have changed all acronyms in the manuscript from ADE to ABE. We have also changed the acronyms from ADE to ABE. All capitalization of first letters of acronyms have been revised. SC5: Introduction (lines 44-46): really confused, please rewrite and simplify it...suggestion "Human influenced historical events, such as plants and animals' domestication or metallurgy, have been responsible for changes in natural landscapes"; Response: We have changed the sentence as recommended. Please see line 71-72. Human influenced historical events, such as plants and animals' domestication and metallurgy, have been responsible for changes in natural landscapes (Peverill et al., 1999; Howard, 2017). 9. SC6: Intro-

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duction (lines 47-51): vide supra...suggestion "Many human activities are responsible for soil alteration; a blatant example is the creation of dark cultural horizons, mainly termed as archaeological black earths (ABE). They usually belong to anthropogenic soils, classified as Anthrosols (REF.) or termed as HAHT (human-altered and human-transported) soils (Soil Survey Staff, 2015). ABE formation consisted in a deliberate and/or unintentional accumulation of layers as consequence of settlement activities, wastes deposition, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. Such anthropogenic soils are usually characterized by higher concentrations in macro- (N, P) and micronutrient (EXAMPLES), that determines a difference in terms of main physical-chemical properties in comparison to neighboring (natural) soils"; Response: We have revised the statements as recommended above. Please see line 73-81. Many human activities are responsible for soil alteration; a blatant example is the creation of dark cultural horizons, mainly termed as archaeological black earth (ABE). They usually belong to anthropogenic soils, classified as Anthrosols (Howard, 2017; World Reference Base (WRB), 2015) or termed as HAHT (human-altered and human-transported) soils (Soil Survey Staff, 2015). ABE formation consisted of a deliberate and/or unintentional accumulation of layers because of settlement activities, wastes deposition, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. Such anthropogenic soils are usually characterized by higher concentrations in macro- (e.g., N, P, K, and Ca) and micronutrient (e.g., Mn, Cu, and Zn), that determines a difference in terms of main physical-chemical properties in comparison to neighboring (natural) soils"; (WinklerPrins, 2014; Nicosia et al., 2017) 10. SC7: Introduction (general comment): please always avoid the use of group of references after every sentence. Better using max 2 references after every important statement Response: We have tried to use maximum of 2 references at the end of each important statement throughout the manuscript. 11. SC8: Line 52: "ADEs are physically characterized by black, dark brown, or dark grey color", please add a reference; Response: We have added a reference to the sentence as suggested. Please see line 82. Archaeological black earths are physically characterized by black, dark

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brown, or dark grey color (Asare et al., 2020a, b).

12. SC9: Line 57: delete "probably"; Response: We have deleted "probably" and many others from the manuscript. For confirmation, please see for example line 88-89. Thus, ABEs can hardly develop in semi-arid and arid regions because of the high decomposition rate of accumulated organic matter. 13. SC10: Line 82: "Amazonian Dark Earth, African Dark Earth, European Dark Earth" please vide supra Response: We used the generic name for these types of ABE's for clarity to the readers. Also, these names are commonly used Literature. 14. SC11: Lines 99-102: "Terra preta is found on a variety of soil types such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols, and Podzols classified according to World Reference Base (WRB) for Soil Resources (Lehmann et al., 2003b)" badly organized sentence. Suggestion: "According to Lehmann et al. (2003) terra preta is found on a variety of soil reference groups such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols (WRB, 2015); Response: We have revised the sentence as recommended. Please see line 132-133. According to Lehmann et al. (2003b), Terra preta is found on a variety of soil reference groups such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols (WRB, 2015).

15. SC12: Lines 103-104: please explain the reasons why of such an important outcome; Response: Most of these prehistoric peoples lived in small groups along the rivers and lakes. For their daily activities, they discard waste (especially organic waste) and potteries around their residence which mainly explain the smaller size of terra preta in these areas. These areas used for habitation or intensive use can accumulate refuse overtime, forming midden-like mound deposits made up of perishable organic refuse and more durable waste, such as ceramic, lithic, faunal, and charred botanical remains. 16. SC13: Lines 104-105: "and located in some geographical regions from which surrounding areas can be observed (Sombroek, 1966)"...ambiguous and unclear sentence. What you mean?; Response: We have reformulated this sentence to make it clearer. Please see line137-139. The areas where this soil usually occurs are

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well-drained, and near running water (Sombroek, 1966). However, Terra preta is not only restricted to areas near rivers but also occurs at higher elevations (Smith, 1999).

17. SC14a: Line 133: please be more specific. Add some quantitative comparison, otherwise it's too generic statement; Response: We have made some quantitative comparisons as suggested. Please see lines 170-172. Dark earths in Liberia and Ghana contained significantly ($p < 0.01$) higher plant-available P (280 mg kg⁻¹), (150 mg kg⁻¹), respectively, compared to their respective (60 mg kg⁻¹and 20 mg kg⁻¹) surrounding soils. 18. SC14b: general comment: please, when you refer to a specifically historical period the beginning and the end must be indicated; Response: We have indicated where possible specific dates of historical periods indicated in the manuscript. Please see for example Line 175. European dark Earth (EDE) is mostly found in the Roman (27 BC – 476 AD) or post-Roman urban contexts observed predominantly, if not exclusively, in Europe 19. SC15: line 178: since the two "hypotheses" are completely complementary, why not suggesting that TP are formed by a unique combination of factors rather than two "hypotheses"? You must write something new, not only reporting already existing ideas; Response: We have reformulated these statements to make them clearer. Please Line 218-220. Terra Preta is formed by a unique combination of intentional management of the soil for farming and unintentional outcome of human occupations and discard of wastes with various inputs of organic and inorganic materials. 20. SC16: lines 188-191: too vague sentence. Be more specific by a deeper investigation of such important questions; Response: The sentences have been reformulated to provide a deeper meaning. We explained the intentional and unintentional activities that lead to the formation of Terra preta. Please see lines 229-235. Also, the repeated slash-and-burn of abandoned settlement sites could have produced Terra preta (Denevan, 1998). Several anthropogenic activities, e.g., the use of low heat, smoldering fires for food and pottery preparations, and spiritual reasons contribute to biochar accumulation or biochar amendments to home gardens, leading to the formation of Terra preta (Glaser et al., 2001). Thus, Terra preta formation is a combination of both unintentional soil modification as well as intentional amendments to improve

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small-scale home gardens. Therefore, this explains why the majority of Terra preta occupy a relatively smaller land size. 21. SC17: lines 195-202: please specify which kind of genetic horizon could be related to proposed classification (Ap, O, L?); Response: We have provided the generic horizon for the classification in the manuscript. Please see line 233-237. According to Ricigliano, (2011) the profile of Terra preta can be physically divided into three; i) horizon A, representing a deep, dark, and nutrient-rich layer with an abundance of pottery fragments, lithics, and charcoal. ii) horizon B/B1, which is a transitional horizon with a large quantity of ped and root linings thickly coated in organic matter, and iii) the third horizon (B2) representing more thinly coated ped due to a lower percentage of organic matter with the soil lighter in color 22. SC18a: lines 203-207: again, too much generic sentence. Please add some quantitative outcomes. You talk about fertility, generally stating that it is higher in TP soils. How much higher? Can you specify N, P or micronutrients concentrations in TP vs natural surrounding soils? Response: We provided quantitative values about the higher fertility of Terra preta. Please see lines 246-249. Moreover, Kern et al. (1996) reported (in mg kg⁻¹) 4900, 1810, 634, 393, and 208 total content of P, Ca, Mg, Mn, and Zn in Terra preta in an archeological site in Quatipuru, Pará, Brazil compared to P, 100; Ca, 500; Mg, 1000; Mn, 1000; Zn, 90; in control (Malavolta, 1976). On the same site, the fertility of the Terra preta was confirmed by 700 mg kg⁻¹ extractable P (32% of total P) compared to < 5 mg kg⁻¹ in control (Lehmann et al., 2003a).

23. SC18b: line 212: again (vide supra) ...no Cation Exchange Capacity but cation-exchange capacity...be consistent along the whole paper; Response: We have revised this throughout the manuscript 24. SC19: line 218: which kind of nutrient? How much? Why? Response: We have given detailed explanation to this statement in the manuscript. Please see line 256-260. The C compounds in charcoal form loose chemical bonds with soluble plant nutrients so they are not as readily washed away by rain and irrigation. Even though charcoal addition to the soil has the potential to bind up N, it may not necessarily provide essential nutrients to the soil. It is, therefore, important to add a nutrient source, e.g., K and Mg along with charcoal amendments

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due to charcoal's high C: N ratio (Tenenbaum, 2009). 25. SC20: lines 219-220: I know Brazil, but most of readers probably not...so why do you think that readers could be familiar with "Greenhouse Facilities of Embrapa Amazônia Occidental" terms? Please clearly explain it; Response: We have reformulated this sentence to provide clearer explanation. Please line 261-262. Moreover, Lehmann et al. (2003a) studied Terra preta in Embrapa Amazônia Occidental, Manaus, Amazonas, Brazil 26. SC21: lines 222-236: again.... too much generic. Comparisons are made from a qualitative point of view only. Some example in terms of quantitative comparisons must be reported. Additionally: Have such studies demonstrated a significance difference between TP vs natural soils? Because, if it was merely a speculative observation it must be ignored; Response: We have rewritten this part of the manuscript to include quantitative comparisons. Please see lines to 268-282.

27. SC22: lines 237-239: thanks for pH and CEC values...the first quantitative outcome reported in your review!; Response: Thank you too 28. SC23: paragraph from 3.2 till to 3.4: please, add some quantitative results...statement such as "store 200–300% more organic carbon than their surrounding soils" are not enough. Indeed, as previously underlined, I need to know if such a comparison was of statistical significance, otherwise you must ignore it; Response: We have given values from paragraph 3.2 to 3.4. For example, from line 298-300. They determined from 400-450 Mg ha⁻¹ organic matter stock in the AfDEs, representing enrichment approximately 200 – 300% compared to the surrounding soils (120-150 Mg ha⁻¹). 29. SC24: paragraph 4: I don't understand the reasons why for such a paragraph. In most of its parts it replies already previously reported matters. Additionally, what about the authors opinion on such specific items? This paragraph has an intriguing title, but the content is characterized by a totally loss in terms of novelty and new ideas; Response: We have combined this paragraph with the discussion. We have also reformulated and given detailed opinions on all the items explained earlier in the manuscript. 30. SC25: Discussion: I don't understand the reasons for separating P3 from P5. I strongly suggest authors combining the two sections avoiding redundancy. This could improve paper readability and attractiveness;

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Response: We have combined both sections for clarity. Please see lines 403-477 31. SC26: Conclusions: too long. Be more focused on novelty aspects only. Please avoid punctuation, is a review paper not a technical report. Response: We reformulated the conclusions as recommended. All punctuations have been removed accordingly, and are now more focused on the novelty of the manuscript.

Origin, distribution, and characteristics of Archaeological black earth soils- A review
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Abstract Archaeological black earth (ABE) can be classified as a layer of anthrosol (syn. anthroposol) visually characterized by black color mainly due to homogenous charcoal inclusion, and substantial enrichment by nutrients compared to surrounding soils. The study aimed to provide a detailed overview of the variability, distributions, and characteristics of ABEs relating to their classifications as well as the physicochemical properties. Archaeological black earth is distributed from the tropics (Amazonian Terra preta, African dark earth), moderate climatic zones (European dark earth) up to the Arctic (kitchen middens). All the types of ABE developed as a result of deliberate and/or unintentional deposition of domestic and occupational wastes, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. ABEs exhibit optimum C: N ratio for effective mineralization, stable organic matter content, and higher CEC compared to surrounding soils. Archaeological Black Earths are characterized by slightly acidic to neutral soil reactions and a substantially enriched by C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, Rb, and Ba in comparison to surrounding control. The unclear

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remains the level of ABEs enrichment by these elements as enrichment factors for different elements are based on different analytical approaches from plants-available up to total contents in the soil. Although generally highly productive, comparison of herbage production and crop yields between ABEs and natural soils are still rare. The distribution and persistence of anthropogenic activities leading to the formation of ABEs indicate that they are subject to continual formation.

Keywords Anthrosol; Biomass ashes; Charcoal; Physicochemical property; Terra Preta

1. Introduction Human influenced historical events, such as plants and animals' domestication and metallurgy, have been responsible for changes in natural landscapes (Peverill et al., 1999; Howard, 2017). Many human activities are responsible for soil alteration; a blatant example is the creation of dark cultural horizons, mainly termed as archaeological black earth (ABE). They usually belong to anthropogenic soils, classified as Anthrosols (Howard, 2017; World Reference Base (WRB), 2015) or termed as HAHT (human-altered and human-transported) soils (Soil Survey Staff, 2015). ABE formation consisted of a deliberate and/or unintentional accumulation of layers because of settlement activities, wastes deposition, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. Such anthropogenic soils are usually characterized by higher concentrations in macro- (e.g., N, P, K, and Ca) and micronutrients (e.g., Mn, Cu, and Zn), that determines a difference in terms of main physical-chemical properties in comparison to neighboring (natural) soils. (WinklerPrins, 2014; Nicosia et al., 2017). Archaeological black earth soils are physically characterized by black, dark brown, or dark grey color (Asare et al., 2020a, b). However, in some regions, soils from past human activities are light without any accumulation of black soil organic matter. For example, although the large-scale accumulation of P, K, S, Zn, and Cu were in comparison to adjacent rangelands and arable fields, at Tel Burna in Israel, even more than 2000 years after its abandonment, the color of the soil was light gray (Šmejda et al., 2017). Thus, ABEs can hardly develop in semi-arid and arid regions because of the high decomposition rate of accumulated organic matter. The depth of the ABE

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horizon normally ranges from 0.4 to 0.8 m and can extend up to 1m or more (Courty et al., 1989; Macphail et al., 2003), with increasing depth indicating increasing longevity and intensity of settlement activities. Archaeological black earth soils have been studied by many authors (Runge, 1973; Mücher et al., 1990; van Smeerdijk et al., 1995) but were previously limited to visual descriptions of different organic and inorganic inclusions, archaeological features, artifacts, and post-depositional modifications. More recently, micromorphological analyses were used to determine the variability of ABEs concerning the position in local catena's, parent materials, and broader landscape locations (e.g., Glaser et al., 2003a, 2003b; Woods et al., 2009). Other studies have emphasized the timescales involved in the creation of ABEs taking hundreds of years (Richter, 2007; Kawa and Oyuela-Caycedo, 2008). Today, multi-elemental techniques are used to quantify different elements in ABEs to trace specific ancient anthropogenic activities connected with the accumulation of these elements. For example, using different analytical tools such as X-Ray florescence (XRF) spectrometry for the determination of near-total contents of elements, inductively-couple plasma optical emission spectroscopy (ICP-OES) in connection with different extraction procedures for estimation of plant available up to total contents of elements (Nicosia et al., 2012). Although many papers studying ABEs are available from different regions, a review summarizing the distribution, evolution, and properties of different ABEs has never been published according to our knowledge. The aim of this review was, therefore, i) to provide an overview of different types of ABEs and their distributions, ii) to describe their physico-chemical properties, and iii) to identify under-studied questions for the future development of new research activities.

2. Historical characterization of archaeological black earth

This part of the review discusses the widely studied ABEs from the tropics up to the arctic zones; Amazonian Dark Earth, African Dark Earth, European Dark Earth, and kitchen middens (middens). Except for middens, the other types have been designated by their regional names. The geographical distribution of ABEs motivated the compi-

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lation of different types from different parts of the world (Fig. 1). The black color of all the ABEs is anthropogenically influenced and does not contradict natural dark soils.

2.1. Amazonian Dark Earth Amazonian Dark Earth is attributed to the vanished complex civilization that once thrived during the Pre-Columbian settlements in the Amazon regions of South American. Recorded use of this soil date at least 5000 Cal Years BP, with the majority forming between 1000 – 2000 Cal Years BP (Whitehead et al., 2010). Statistical modeling indicates that more than 150 000 km² representing 3.2% of the Amazon forest may harbor Dark Earth sites (McMichael et al., 2014). Amazonian Dark Earth soil is most widely studied in Brazil where they occupy relatively large areas with thick altered soil mantles and higher chemical fertility than the surrounding soils not affected by anthropogenic activities (Corrêa, 2007). These sites are known by designations such as black earth (Terra preta), Indian black earth (Terra preta de Indio), anthropogenic black earth (Terra preta antropogenica), and archaeological black earth (Terra preta arqueologica) collectively termed as Amazonian Dark Earths (Lehmann et al., 2003b). According to Lehmann et al. (2003b), Terra preta is found on a variety of soil reference groups such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols (WRB, 2015). Their extent is not large, most patches range in size from 2 to 350 ha with the majority being at the smaller end of that range. Most of these pre-historic people lived in small groups along the rivers and lakes. The size of Terra preta usually depends on the number of inhabitants and duration of settlement in the area (Smith, 1980) The areas where this soil usually occurs are well-drained, and near running water (Sombroek, 1966). However, Terra preta is not only restricted to areas near rivers but also occurs at higher elevations (Smith, 1999). Past human activities have significantly distinguished the elemental composition of these soils compared to neighboring soils. Terra preta rarely appears as individual classes of soil on soil maps of the region because of their generally small individual extent but are included in more spatially extensive soil classes.

2.2. African Dark Earth African Dark Earth (AfDE) are found around edges of nucleated

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villages and ancient towns in tropical regions of Africa (Solomon et al., 2016), typically in rain forest suggesting that verdant rainforest is long-abandoned farmlands and settlement sites enriched by the wastes created by ancient humans. In a first-time analysis of indigenous soil management system in West Africa, radiocarbon dating (14C) of black C (charcoal) found in most identified AfDEs indicated that these soils developed ca 115 to 692 cal Years BP (Solomon et al., 2016) the only dated AfDEs in Africa so far. The discovery of pottery fragments and charred remains of burnt wood from fires set by humans, along with organic macro-remains from crop residues, animal, and bones have been identified as components of AfDE (Asare et al., 2020a). However, Frausin et al. (2014), reported that only particular human activities are responsible for AfDE formation and are highly differentiated by gender. Women are directly engaged in the deposition of charred organic materials from oil palm processing and potash production which are the major contributing activities in the formation processes. AfDEs are spatially distributed across most tropical regions of the African landscape, especially rain forest zones of Ghana, Cameroon, Chad, Guinea, Congo, Malawi, Sierra Leone, Liberia, and rarely in Ethiopia (Fairhead and Leach, 2009) engineered mostly by shifting households and settlement practices. In a recent study by Asare et al. (2020a), the authors identified the influence of past settlement activities, including burning observed from ashy deposits and burnt palm kernel shells in the formation of AfDE in Ghana. Although several discoveries of charred materials and pottery fragments were identified in AfDEs by Frausin et al. (2014), their study was limited to the factors of formation processes and did not determine the age of these objects. However, oral histories and landscape mapping confirmed that these indigenous soil management practices created AfDE in ancient times and has continued up to the present day, probably older than had been known (Fraser et al., 2014; Solomon et al., 2016). Inhabitants of identified AfDE sites from ethnographic accounts lived several thousand years in nucleated villages with subsistence focused on farming, hunting, etc. Thus, most studied AfDEs have rural origins (Frausin et al., 2014) unlike European dark earth and Terra preta which traces its origin from ancient civilization (Nicosia et al., 2012; WinklerPrins,

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2014). Until now, there are so studies reporting the prehistoric origin of AfDE. According to (Solomon et al., 2016) local inhabitants of areas with human-impacted dark earth in a study in Ghana and Liberia reported high crop yields compared to the surrounding soils. Dark earths in Liberia and Ghana contained significantly ($p < 0.01$) higher plant-available P (280 mg kg⁻¹), (150 mg kg⁻¹), respectively, compared to their respective (60 mg kg⁻¹ and 20 mg kg⁻¹) surrounding soils (Solomon et al., 2016).

2.3. European Dark Earth European dark Earth (EDE) is mostly found in the Roman (27 BC – 476 AD) or post-Roman urban contexts observed predominantly, if not exclusively, in Europe. In an archaeological context, EDE indicates urban dark-colored, poorly stratified units, often formed over several centuries, frequently rich in anthropogenic remains such as biomass ashes, bricks, bones, charcoal, mortar, tiles, and pottery (Figure 3c). Micromorphological analysis of EDEs has indicated that dumping of wastes (house sweeping, hearth functioning and maintenance, and more especially food preparation) is an activity commonly identified to contribute immensely to the formation of EDE (Nicosia et al., 2012). The latter has often developed from middening deposits, for example in open areas or within abandoned house shells. Several pedological studies on EDE has been conducted in most European countries in the 1980s and 90s. However, maiden studies appeared in early 1980 in Britain and later in Italy where the expression Terre Nere. In France, EDE studies on Terres Noires date back to the early 1990s (Gebhardt, 1997). The earliest studies on EDE in Belgium have been carried out since 1996 in the city of Ghent and later in Brussels (Stoops et al., 2001; Devos et al., 2016). Several articles based on comparisons between EDEs contexts in different European countries were published (Macphail, 2014; Nicosia and Devos, 2014; Asare et al., 2020b).

2.4. Kitchen Midden Kitchen middens are localized patches of dark-colored earth with artifact inclusion resulting from the deliberate deposition of food remain, domestic materials such as broken and exhausted tools as other human occupations (Hirst, 2017). Middens are named according to their major composition, e.g., bone midden. How-

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ever, kitchen maiden may contain both a high proportion of bones and shells. Middens are found everywhere humans have lived and have been connected to the Mesolithic period, ca 12000 Cal Years BP (Hirst, 2017). The size of a kitchen midden is a function of population size and the length of time the site was active. Kitchen midden usually develops in non-urban areas, where people discard food and other domestic waste into the soil at the same place (Howard, 2017). Over many years or centuries of waste disposal, midden developed a thick black, organic-rich topsoil usually containing animal bones, mollusk shells, charcoal, ash, etc. and can be in the form of a mound, a pit, or a layer in stratigraphic of the soil. Midden may represent individual periods of settlement at a place. For instance, the different layers of kitchen midden found in Qajaa, Greenland represent three different periods of settlement (Hollesen et al., 2013). The first 120 cm thick layer from the bottom represents the Saqqaq people who lived at the site from around 2000 – 1000 BC, followed by 20 – 30 cm peat without evidence of human activity (1000 – 400 BC). This was overlaid by a 2 – 30 cm thick layer representing the hunters of the Dorset people living in the area from about 400 – 200 BC. The uppermost archaeological layer (in some places up to 1 m thick) has been dated to represent the last immigration of Eskimos to Greenland (The Thule people; 1200 –1750 AD).

3. Physicochemical characteristics of Archaeological black earth Generally, ABEs have been reported to exhibit unique physical and chemical characteristics in comparison to their neighboring soils. This section is an overview of the physicochemical attributes of the different types of ABEs discussed above.

3.1. Physicochemical properties of Amazonian dark earth Terra Preta is formed by a unique combination of intentional management of the soil for farming and unintentional outcome of human occupations and discard of wastes with various inputs of organic and inorganic materials (Glaser et al., 2001). There is a reported possibility that agricultural practices in home gardens contributed to the genesis of Terra preta (Hecht 2003; Schmidt and Heckenberger, 2009). In recent times, midden areas are used as home gardens or home gardens are used as trash areas by indigenous groups in the

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Amazon basin such as the Ameridians. Amendments of biochar to home gardens are responsible for the high amounts of black C. Therefore, Terra preta genesis can be explained by formation from midden areas and home garden agriculture as also practiced today (Fig. 2). Also, the repeated slash-and-burn of abandoned settlement sites could have produced Terra preta (Denevan, 1998). Several anthropogenic activities, e.g., the use of low heat, smoldering fires for food and pottery preparations, and spiritual reasons contribute to biochar accumulation or biochar amendments to home gardens, leading to the formation of Terra preta (Glaser et al., 2001). Thus, Terra preta formation is a combination of both unintentional soil modification as well as intentional amendments to improve small-scale home gardens. Therefore, this explains why the majority of Terra preta occupy a relatively smaller land size. According to Ricigliano, (2011) the profile of Terra preta can be physically divided into three; i) horizon A, representing a deep, dark, and nutrient-rich layer with an abundance of pottery fragments, lithics, and charcoal. ii) horizon B/B1, which is a transitional horizon with a large quantity of ped and root linings thickly coated in organic matter, and iii) the third horizon (B2) representing more thinly coated ped due to a lower percentage of organic matter with the soil lighter in color. However, in the field, Terra preta is identified by unusual features for Amazonian upland soils, such as topsoil with dark matrix colors (dark brown to black) at a variety of depth and presence of potsherds and lithic artifacts corroborated with the homogenous high amount of charcoal (Fig. 3a). The most extraordinary chemical characteristics of Terra preta is their high fertility because they have persisted in environments that generally have high rainfall and high humidity which facilitate soil organic matter mineralization and nutrient leaching. Terra preta has been reported having 2 to 3 times increased content of Ca, K, Mg, Mn, Cu, and Zn in comparison to surrounding soils since their discovery in the 1860s and 70s (Smith, 1980; Glaser, 2007; Winkler-Prins, 2014). Moreover, Kern (1996) reported (in mg kg⁻¹) 4900, 1810, 634, 393, and 208 total content of P, Ca, Mg, Mn, and Zn in Terra preta in an archaeological site in Quatipuru, Pará, Brazil compared to P, 100; Ca, 500; Mg, 1000; Mn, 1000; Zn, 90; in control (Malavolta, 1976). On the same site, the fertility of the Terra preta was con-

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firmed by 700 mg kg⁻¹ extractable P (32% of total P) compared to < 5 mg kg⁻¹ in control (Lehmann et al., 2003a). The unique nature of high C content in Terra preta is the key to the stability of the organic matter. The C found in Terra preta is aromatic (black or pyrogenic carbon) and other organic materials (biochar) that are likely a consequence of the incorporation of charcoal into the soil (Golchin et al., 1997). This initiates a set of biological and chemical processes that have confirmed increased soil organic matter, microbial biomass, and diversity, cation-exchange capacity (CEC), pH, and nutrient retention (Lehmann et al., 2003a, b; WinklerPrins, 2014). Terra preta has been reported to contain C content of up to 150 g kg⁻¹, as opposed to 20 to 30 g kg⁻¹ in surrounding soils (Novotny et al., 2009). The C compounds in charcoal form loose chemical bonds with soluble plant nutrients so they are not as readily washed away by rain and irrigation. Even though charcoal addition to the soil has the potential to bind up N, it may not necessarily provide essential nutrients to the soil. It is, therefore, important to add a nutrient source, e.g., K and Mg along with charcoal amendments due to charcoal's high C: N ratio (Tenenbaum, 2009). Moreover, Lehmann et al. (2003a) studied Terra preta in Embrapa Amazônia Occidental, Manaus, Amazonas, Brazil and reported significantly higher contents of C (84.7 g kg⁻¹), P (318.4 mg kg⁻¹), and Ca (32.8 mmolc kg⁻¹) compared to 39.7, 8.1, and 14.7, respectively, of same elements in surrounding soil. The content of available P was 318.4 mg kg⁻¹ compared to 8.1-24.1 mg kg⁻¹ in control, even with the addition of mineral fertilizers, manure, and charcoal. Additionally, increased contents of plant-available P (average of 175 mg kg⁻¹) in 29 Terra preta sites formed on oxisols and ultisols compared to 21.83 mg kg⁻¹ of naturally occurring P in these soils. have been reported (Smith, 1980). The Ca content in these sites was comparably higher averaging 21 mg kg⁻¹ and is also consistent with Sombroek's (1966) studies in five Terra preta sites where Ca ranged up to 109 mg kg⁻¹. In a similar study on the chemical signatures of Terra preta by Kern (1988), anomalous increase by total P (320 mg kg⁻¹), Zn (56 mg kg⁻¹), and Mn (686 mg kg⁻¹) contents compared to their respective surrounding soils of 46 mg kg⁻¹P and 0 Zn and Mn were recorded near the shores of the Trombetas-Nhamundá River. Kern (1988) correlated these data

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with the former human occupation of the area. Similar enrichment was obtained for two Terra preta sites in Santarém, Pará state, Brazil, where the contents of total P (366 – 460 mg kg⁻¹), Zn (21 - 26 mg kg⁻¹), and Mn (25 - 32 mg kg⁻¹) was significantly higher in comparison to respective surrounding soils of 54-772 mg kg⁻¹ P, 2 - 4 mg kg⁻¹ Zn, and 3 - 5 mg kg⁻¹ Mn (WinklerPrins and Falcão, 2010)). Some authors have worked on the chemical content of fragmented potteries found in the Terra preta in the Amazon Basin (Da Costa et al., 2011; Costa et al., 2013). Most of these studies revealed that areas with the highest density of pottery fragments coincide with the highest contents of elements such as Zn, Cu, Mn, Ba, and Sr. These elements are indicative of human occupation and thus related to domestic units such as cabins, food storage, food preparation, and food consumption areas. Thus, Terra preta relates to increased contents of organic C, P, Ca, Mg, Mn, and Zn regardless of soil type on which it was formed in contrast to the usually highly weathered and nutrient-poor surrounding soils. Terra Preta is characterized by reduced acidity with pH usually ranging from 5.2 to 6.4 (Falcão et al., 2009; WinklerPrins, 2014) in comparison with surrounding soils with pH ranging from 3.0 to 4.2 (Souza et al., 2016). Terra preta is characterized by higher moisture-holding capacity and CEC in comparison with surrounding soils (Sombroek, 1966; Smith, 1980). Souza et al. (2016) recorded higher CEC ranging from 33.4 to 41.9 cmol dm⁻³ in Terra preta in comparison to only 14.2 cmol dm⁻³ in the surrounding soil. The combination of land use and ecological factors that led to the formation of Terra preta is still not known with precision.

3.2. Physicochemical properties of African dark earth Processes that lead to the formation of AfDE are quite similar to those of Terra preta except for certain activities that are peculiar to African regions. Therefore, AfDE is human-made analogous to Amazonian Terra preta yet subject to the continual formation. Although the physical characteristics of AfDEs are analogous to those of Terra preta, representative profile in comparison to other surrounding profile indicates that AfDE is dark-colored with the accumulation of pyrogenic carbon (PyC) in these black piles of the earth extending to a depth of 1.80 m (Fig. 3b). Studies carried out by Solomon et al. (2016) in Ghana and Liberia identified

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that AfDEs have a higher content of nutrients in comparison to surrounding soils. They determined from 400-450 Mg ha⁻¹ organic matter stock in the AfDEs, representing enrichment approximately 200 – 300% compared to the surrounding soils (120-150 Mg ha⁻¹). Plant-available N and P contents in the arable layer (0-0.02 m) ranged from (in mg kg⁻¹) 1-3 and 150-400, respectively, compared to about 0.5-1.9 and 5-60 in the surrounding soils. The contents of Ca, K, and Mg were substantially higher in AfDE than in surrounding soils (Solomon et al., 2016). They recorded a pH range from 5.6 to 6.4 (moderately to slightly acidic) quite analogous to those noted in many studied Terra preta compared to 4.3-5.3 (very strongly to strongly acidic) in the control. There was significantly higher pyrogenic carbon (4.94-37.74%) and cation-exchange capacity (120-150 mmolc kg⁻¹) in the AfDE sites, representing 2 – 26 and 1.4 – 3.6, respectively, enrichment compared to surrounding soils. And this contributed to the retention of the elements. Except for increased plant-available N which has been recorded in the study of AfDEs, the high pH, CEC, and increased content of C, P, Ca, Mg mimics that of Terra Preta and other types of ABEs. In a recent study of AfDE in Ghana, the content of total P, K, Ca, and Mn was (in %) 0.16- 0.65, 0.8- 1.44, 0.9-0.02, 0.08- 0.27, respectively, higher than the control (Asare et al., 2020a). In addition to substantially higher plant-available P, K, Ca, S, Fe, Cu, and Zn in the AfDE compared to the control. The authors further recorded a significantly higher pH ranging from 6.1-6.9 in the AfDE compared to 4.4 in the control. Hence, the retention of the elements in the AfDE is related to reduced soil acidity. Although AfDEs have been identified in small patches of landscapes in many African countries, their classification has generally been based only on physical description lacking proper dating and detailed chemical analysis.

3.3. Physicochemical properties of European dark earth Pedological studies of EDE have been based on the topsoil with very little knowledge on the subsoil. The physical description of EDE usually divides the depth of the soil into four distinct horizons with the upper horizon mostly made of midden materials in the form of charcoal, shell, bone, plaster, bricks, etc. (Table 1; Courty et al., 1989). Furthermore, Courty et al. (1989), categorized EDE from their studies in London into two stratigraphic units; the

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lower 'pale Dark Earth' unit and the upper 'Dark Earth' unit. The pale Dark Earth unit was found on the relict of Roman floor levels which contained Roman coins and burials and was crosscut by later Roman features including debris from burning, collapse, and decay of buildings. The upper layer was typically 20 to 90 cm thick but ranged up to 2 m in thickness and was characterized by blackish color (Fig. 3c). Notwithstanding, the stratigraphical classification (cultural layers) of EDE can be connected with different past settlements from different archeological timelines. Another important characteristic feature of EDE is the high degree of bioturbation observable in the thin section. On the other hand, part of the EDE results from soil formation on grassland, pasture, or abandoned areas in urban or proto-urban contexts. Typical features are enhanced organic matter, biogenic porosity, and earthworm granules. Human activities such as house sweeping, hearth functioning and maintenance, food preparation, construction, leatherworking, manuring, quarrying, metal production among others have contributed to the formation of EDE. Butchery and leatherworking waste have been reported by Stoops et al. (2001) from the Dark Earth in the center of Ghent, Belgium, and is a typical component at the London Guildhall (Macphail et al., 2008). Nicosia et al. (2017) reported that pedo-features associated with Dark Earth are mostly the outcomes of the formation of carbonates, Fe/Mn (hydr) oxides, and/or phosphates. The most common carbonate pedo-features are typical calcite nodules and hypo-coatings, the calcite deriving from the natural parent material (e.g., calcareous alluvium), or the dissolution of ashes, plaster, or mortar. The presence of fecal material such as latrine wastes and coprolites, charcoal, pottery, and enhanced values of P, organic matter, and exchangeable basic cations in Brussels confirms the use of manure (Devos et al., 2009). Most EDEs have high biomass ashes and contain brick earth and mortar fragments. The availability of P and other elements are from the decomposition of plant materials, excrements, urine, ashes, bones or fish bones, and charcoal. Courty et al. (1989) reported an extremely high content of total P between 1.6 to 2.6% in London impacted by bone, feces, or plant decomposition. Nicosia et al. (2012) in using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS) in Dark Earth in Florence, Italy re-

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vealed that the neoformations consisted predominantly of calcium-iron phosphates or calcium phosphates with associated iron oxides. They further discussed that there is a limited variability of most of the physicochemical characteristics such as organic C, N, CEC, base saturation, dithionite extractable Fe, and Mn with depth in Dark Earth. Moreover, in comparing dark earth formed beneath the alluvial sediments, the dark earth soil horizons contained from 0.48 – 1.25% organic carbon when compared to the alluvial sediments of 0.43%. Further, N recorded in the dark earth horizons ranged from 0.07 – 0.112% but no content of N was recorded in the alluvial sediments. A pH value ranging from 6.6 to 8.2 has also been reported in EDE by Courty et al. (1989) and Nicosia et al. (2012). In the 10 - 11th century AD, Slavic settlement activities in the Wendland region, Northern Germany created dark patches of soil horizon in the settlement area. Multi-elemental analysis of this soil indicated significantly higher content of C, N, P, Ca, Mg, Na, Fe, Cu, Zn, Mn, Ba and, pH (H₂O) ranging from 5.0 to 6.7 compared to neighboring soil (Wiedner et al., 2015). These soils related to the first millennium AD dark earth from settlement context (often urbanized), which is known from the site in post-Roman Britain (Macphail, 1983) and partly from the migration period and Viking age size in Scandinavia (Wiedner et al., 2015). EDE from an 8th-13th century AD hillfort settlement, Czech Republic was reported of 40, 350, 900, 100, 140, 100, 35, 40, 30 and 90% enrichment by total N (0.3%), P (0.34%), Ca (2.4%), Mn (0.065%), Fe (2.4%), Al (4.8%), Sr (0.012%), Rb (0.011%), Cu (40 mg kg⁻¹), and Zn (110 mg kg⁻¹), respectively, in comparison to the control (Asare et al., 2020b). The soil was 2.5, 2.4, 4.3, and 1.5 times enriched by plant-available (in mg kg⁻¹) P (451), K (384), Ca (7494), and Mg (188), respectively, compared to the control. Although the reduced pH (6.5) contributed to the retention of the elements, physical parameters such as the relatively high fraction of silt and clay and homogenous distribution of charcoal were vital in providing high sorption for the elements.

3.4. Physicochemical properties of Kitchen middens Middens are generally localized sites, ranging from < 0.5 to several hectares in size, and are unrestricted in their distributions. Kitchen middens usually form because of repeated dumping but may be

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created by a single ceremonial feast (Howard, 2017). The kitchen midden is analogous to Terra preta due to their accumulation of abundant archaeological debris and sometimes generically referred to as Dark Earth (Fig. 3d). The dark color of kitchen midden is due to prolonged anthropogenic influence mainly by the accumulation of half-burnt organic matter (Lima, 2001). In some cases, midden environments have excellent preservation of organic materials like wood, basketry, and plant food. Most studied kitchen middens have higher nutrients content in comparison to surrounding soils (Schaefer et al., 2004; Kämpf and Kern, 2005) which can be attributed to the presence of incompletely weathered nutrient sources and abundant pottery fragments. Eberl et al. (2012) observed that human activities including the preparation of pigments explained the obscure distribution of different elements. High P levels were useful to detect middens, but they provided incomplete data and required contextualization by comprehensive archaeological interpretations. Migliavacca et al. (2013) confirmed that high total P content among soil samples ranged from 11409 – 30663 mg kg⁻¹ and organic P content (up to 28423 mg kg⁻¹) was due to the accumulation of organic matter in a garbage hole. The contrast between domestic activities and garbage accumulation is indicated by the highest values of the C: N ratio in the latter. Moreover, in a phosphate analysis in Piedras Negras, Guatemala, Parnell (2001), concluded that areas of highest phosphate content (> 100 mg kg⁻¹) were areas with a high ceramic density as well as bone fragments, charcoal, shells, and artifacts indicative of a kitchen midden. Petry and Bense (1989) studied midden-mound soils in north-eastern Mississippi, USA. They confirmed that these soils were generally enriched in organic C (0.9-1.9%), exchangeable bases, and P (203 – 408 mg kg⁻¹), Ca (11.3 – 15 cmol kg⁻¹), and had wider C: N ratios (16.9 – 22.1) than the natural soil. They had abundant evidence of biological activities, pH ranged from 5.5 to 6.0 compared with pH (H₂O) 5.2 or less in natural soils, and they contained 1 to 5% charcoal in volume. In an analysis of the chemical signature of a late classic Maya residential complex, Guatemala increased content of P, Fe, Sr, Cu, Mn, and Zn coincided with specific pits identified as a midden area (Eberl et al., 2012). However, the content of metals such as Pb and Cd may reflect

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occupational wastes.

4. Discussion The review present for the first-time detailed characterization of different types of ABEs from different geographical locations (Table 2). There are diverse factors that contributed to their formation processes from different geographical locations, which are generally the same in all ABEs. ABEs have stable organic matter stock, optimum C: N ratio for mineralization and release of elements, higher pH, CEC, and contents of C, N, P, Ca, Mg, Mn, Cu, Zn, Sr, and Ba mostly corroborated with a higher amount of charcoal compared to surrounding soils. The accumulation of the elements is predominantly due to the deposition of organic wastes and wood ashes. The depth of ABEs is influenced by the duration and intensity of ancient human activities. Studied ABEs across the world represent nutrient-rich landscapes resulting from ancient human activities. Different types of studied ABEs have the same principle of formation and similar chemical properties. However, many authors have used different methodologies to quantify the elemental composition of ABEs from Africa to arctic regions (Lehmann et al., 2003b; Nicosia et al., 2013; Solomon et al., 2016). These methodological approaches were focused on the quantitative analysis of plants-available nutrients using different extraction approaches or on the total content of elements in the soil using dry analytical methods of XRF. Although different methods were used, there was a clear pattern recorded by all approaches – an enrichment of ABEs by C, N, P, Ca, Mg, Mn, Cu, Zn, Sr, and Ba in comparison to surrounding soils. The question which is still unsolved is how large the enrichment for different elements is and ABEs as every researcher uses a different analytical approach which gives different enrichment factors. In this respect, the total content of elements gives clear enrichment factors as obtained values for different elements are less affected by soil properties and reactions. Plant available contents of elements are generally highly affected by pH; thus, extraction of the plant-available fraction can increase the unreliability of enrichment factors as most elements can relate to soil matrix and they may not be released by extractants. Measurement using XRF and ICP-OES for the total content of the element can be compared since they correlate strongly with high precisions (Šmejda et al., 2018). Different

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types of ABEs have a different date of origin and geographic location as well as other peculiar activities pertinent within the cultural setting of the site where they are formed (Nicosia et al., 2012; Frausin et al., 2014). However, the formation of Terra preta and AfDE are generally more analogous as they both represent human formed soil from the tropical regions especially the rainforest zone in contrast with poorly drained surrounding soils (Sombroek, 1966; Solomon et al., 2016). A scattered range of these soils exist but perhaps have a different designation as observed in some countries in Asia and the arctic regions or not studied at all, especially in some parts of Africa. The deposition of domestic wastes has been noted as a factor in the formation of ABEs. Meanwhile, this is a major factor contributing to the formation of kitchen middens thus, kitchen middens form part of all the types of ABEs. The increased pH and stability of high organic matter content of ABEs provide suitable conditions for the persistence of other elements, high CEC, favorable C: N ratio for effective mineralization to enable higher crop growth. Studies on ancient dark anthroposols using different dating approaches and elemental analysis have generally been conducted in different parts of the world. However, in many studies, the soil may either not be named as a type of ABE or lacked proper dating (Fenger-Nielsen et al., 2018). However, the physicochemical features of such soil are similar to most identified and studied ABEs. In a study by Fenger-Nielsen et al. (2018), in five arctic archaeological sites in Greenland, extractable (in kg m⁻²) P (12.51-29.01), water-extractable nitrate (0.18-0.53), and ammonium (0.47-0.85) were 2 - 6 times higher in dark deposit compared to surrounding soils. The increased content of elements and the black color of soil resulted from past human activities. The cold, wet climate of the Arctic led to the extraordinary preservation of archaeological sites and materials that offer important contributions to the understanding of our common cultural and ecological history (Holleisen et al., 2018). They concluded that soil-vegetation interaction at archaeological sites is markedly different and less affected by the natural environment and regional climate variations. Although such a conclusion was made, crop and herbage production in ancient anthropogenically black soil in comparison to control are not well-known. The formation of ABEs on existing natural dark soils e.g.,

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chernozems has also received a lot of attention recently. In Central Europe, there has been no consensus on the formation of Chernozems as they are not only formed under steppe conditions but may be formed under forest vegetation (Schmidt et al., 2002). Given the extent and agricultural importance of this soil type recent studies indicate that factors including vegetation burning for agricultural purposes and other anthropogenic activities could contribute to the formation of this soil. However, no absolute time and age of chernozems have been stated since radiocarbon dating from charred materials conducted only provided the mean ages of fire events and mean residence time of soil organic matter based on stratigraphic records which provided Holocene age spreading over 3700 years. However, in a study by Carsten and Thomas (2010) on anthropogenic pedogenesis of chernozems in Germany, they concluded that the black C was formed through natural or anthropogenic burning can only be speculated as to the widespread destruction of forests by extended human fire clearance during the Early Neolithic period is rather unlikely. Meanwhile, remarkable evidence exists that Neolithic settlements were mostly situated at the edges of black soil patches confirming the idea that black soils as relics of agriculture (Gehrt et al., 2002; Eckmeier et al., 2007). Therefore, chernozems have completely different formation histories with most of them still under discussion. These observations have raised opportunities for further investigation into their distribution, land-use history, and dating to obtain more conclusive findings. In tropical Asia, in the interior of Borneo, East Kalimantan, Indonesia, preliminary evidence exists that several sites exhibit similar characteristics of Terra preta; riverside location, dark color with few pieces of charcoal (10 cm radius), higher pH, C, P, and Ca, and improved soil fertility in comparison to neighboring soils (Sheil et al., 2012). However, the ages of these soils are yet unknown even though humans have been present in East Kalimantan for 10,000 years (McDonagh, 2003). Ethnographic accounts suggested that swidden farming, which primarily involves slash and burns, and rotational farming was practiced there. The existence of such proves indicate that several patches of ABEs have been left unstudied or unclassified in nucleated abandoned villages, reserve areas as much attention are mostly paid on urban

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dark soils.

5. Conclusions and outlook The study revealed that the types of ABEs (Amazonian Terra preta, African Dark Earth, European Dark Earth, and kitchen middens) are distributed from tropics, moderate climatic zones up to the Arctic regions and relates with past human activities such as slash-and-char and disposition of excrements, shells, bones, and wood ashes. The principles leading to the physicochemical formation of ABEs are similar except for certain human activities peculiar to the cultural setting of the regions. The fertility of ABE is associated with stable organic matter stock, microbial abundance, as well as higher CEC, pH, and nutrient (C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, Rb, and Ba) content. The retention of the nutrients relates to the fraction of the size of soil particles, suitable pH, and homogenous distribution charcoal, predominantly responsible for the black color. There is a strong call for research in the study of some aspect of ABEs. Even with distinguishable features of ABEs, compared to the surrounding soil, not much is known about ABE in some parts of the world, e.g., Asia and North America. The direct estimate of the positive effects of ABE on crop yield in comparison to surrounding soils has been done in few cases only on Terra preta, but not on other ABEs. Even though AfDEs are mostly used for crop production and are reportedly known for high yields, a practical comparison of yields with surrounding soils has not been performed. The opportunities for C sequestration and the reduction of Greenhouse gas emissions in ABEs are potentially important for detailed studies. Hence, systematic research into the origin, chemistry, crop nutrient uptake, production potential, and application of stable isotope analysis of ABEs is necessary to provide better insight and attention to this category of soil.

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DEAD: Deploying the Dead-Artefacts and Human Bodies in Socio-Cultural transformations). This project has also received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 649307.

Reference Asare, M. O., Apoh, W., Afriyie, J. O., Horák, J., Šmejda, L., and Hejcman, M.: Traces of German and British settlement in soils of the Volta Region of Ghana. *Geoder. Reg.* 521, e00270. <https://doi.org/10.1016/j.geodrs.2020.e00270>, 2020a. Asare, M.O., Horák, J., Šmejda, L., Janovská, M., Hejcman, M.: A medieval hillfort as an island of extraordinary fertile Archaeological Dark Earth soil in the Czech Republic. *Eur. J. Soil Sci.* <https://doi.org/10.1111/ejss.12965>, 2020b. Arroyo-Kalin, M., Neves, E. G., and Woods, W. I.: Anthropogenic dark earths of the central Amazon region: remarks on their evolution and polygenetic composition. In: Woods, W. I., Teixeira, W.G., Lehmann, J., Steiner, C., WinklerPrins, A., Rebellato, L. (Eds.), *Amazon Dark Earths: Wim Sombroek's vision*. Springer, Dordrecht, 99 – 125 pp., 2009. Carsten, L., and Thomas, S.: Anthropogenic pedogenesis of Chernozems in Germany? – A critical review. *Quat. Int.*, 243, 273 – 279, <https://doi.org/10.1016/j.quaint.2010.11.022>, 2010. Corrêa, G. R.: Caracterização pedológica de arqueo-antropossolos no Brasil: Sambaquis da Região dos Lagos (RJ) e terras pretas do índio na região do baixo rio Negro/ Solimões. Viçosa, Tese de Mestrado, Universidade Federal de Viçosa, 2007. Costa, J. A., Da Costa, M. L., and Kern, D. C., Analysis of the spatial distribution of geochemical signatures for the identification of prehistoric settlement patterns in ADE and TMA sites in the lower Amazon Basin. *J. Archaeol. Sci.*, 40, 2771 – 2782, <https://doi.org/10.1016/j.jas.2012.12.027>, 2013. Courty, M. A., Goldberg P., and Macphail, R. I.: Soils and micromorphology in archaeology. Cambridge University Press, Cambridge, 1989. Da Costa, M. L., Rios, M. G., da Silva, M. M. C., da Silva, G. J., and Molano-Valdes, U.: Mineralogy and chemistry of archaeological ceramic fragments from archaeological Dark Earth site in Colombian Amazon. *Rem: Revista Escola de Minas*, 64, 17 – 23, <https://doi.org/10.1590/S0370-44672011000100002>, 2011. Denevan, W. M.: Comments on prehistoric agriculture in Amazonia. *Culture and Agriculture*, 20, 54 – 59, 1998. Devos, Y., Nicosia, C.,

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Vrydaghs, L., Speleers, L., van der Valk, J., Marinova, E., Claes, B., Albert, R. M., Esteban, I., Ball, T. B., Court-Picon, M., and Degraeve, A.: An integrated study of Dark Earth from the alluvial valley of the Senne river (Brussels, Belgium). *Quat. Int.*, 460, 175 – 197, <https://doi.org/10.1016/j.quaint.2016.06.025>, 2016. Devos, Y., Vrydaghs, L., Degraeve, A., and Fechner, K.: An archaeopedological and phytolitarian study of the 'dark earth' on the site of Rue de Dinant (Brussels, Belgium). *Catena* 78, 270 – 284, <https://doi.org/10.1016/j.catena.2009.02.013>, 2009. Eberl, M., Álvarez, M., and Terry, R. E.: Chemical signatures of middens at a late classic Maya residential complex, Guatemala. *Geoarchaeology*, 27, 426 – 440, DOI: 10.1002/gea.21415, 2012. Eckmeier, E., Gerlach, R., Gehrt, E., and Schmidt, M., Pedogenesis of Chernozems in Central Europe – A review. *Geoderma*, 139, 288 – 299, 2007. Falcão, N., Clement, C. R., Tsai, S.M., and Comerford, N. B., Pedology, fertility, and biology of central Amazonian Dark Earths. In: Woods, W. I., Teixeira, W.G., Lehmann, J., Steiner, C., WinklerPrins, A., Rebellato, L. (Eds), *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer, Berlin. pp. 213 – 228, 2009. Fairhead, J., and Leach, M.: Amazonian Dark Earth in Africa. In: Woods, W.I., Teixeira, W.G., Lehmann, J., Steiner, C., WinklerPrin, C.A., Rebellato L. (Eds), *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer, Dordrecht, 265 – 278 pp., 2009. Fenger-Nielsen, R., Hollesen, J., Matthiesen, H., Andersen, E.A.S., Westergaard-Nielsen, A., Harmsen, H., Michelsen, A., and Elberling, B.: Footprints from the past: the influence of past human activities on vegetation and soil across five archaeological sites in Greenland. *Sci. Tot. Environ.* 654, 895 – 905, <https://doi.org/10.1016/j.scitotenv.2018.11.018>, 2019. Fraser, J. A., Leach, M., and Fairhead, J.: Anthropogenic dark earth in the landscapes of upper Guinea, West Africa; Intentional or inevitable? *Annals of the Association of American Geographers* 104, <https://doi.org/10.1080/00045608.2014.941735>, 2014. Frausin, V., Fraser, J. A., Narmah, W., Lahai, M. K., Winnebah, T. R. A., Fairhead, J., and Leach, M.: "God made the soil, but we made it fertile": Gender, knowledge, and practice in the formation and use of African Dark Earths in Liberia and Sierra Leone. *Hum. Ecol.*, 42, 695 – 710, 2014. Glaser, B., Haumaier, L., Guggenberger, G., and Zech,

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W.: The “Terra preta” phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, 88, 37 – 41, DOI 10.1007/s001140000193, 2001. Glaser, B., Guggenberger, G., Zech, W., and Ruivo, M. L., Soil organic matter stability in Amazonian Dark earths. In: Lehmann, J., Kern, D.C., Glaser, B., Woods W.I. (Eds). *Amazonia Dark Earths: Origin, properties, and management*. Kluwer Academic Publishers, Dordrecht, pp. 141 – 158, 2003a. Glaser, B., Guggenberger, G., and Zech, W.: Organic chemistry studies on Amazonian Dark Earths. In: Lehmann, J., Kern, D.C., Glaser, B., Woods W.I. (Eds). *Amazonia Dark Earths: Origin, properties, and management*, Kluwer Academic Publishers, Dordrecht, pp. 227 – 241, 2003b. Glaser, B.: Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the 21st century? *Philosophical Transactions of the Royal Society B: Biological Science*, 362, 187 – 196, DOI: 10.1098/rstb.2006.1978, 2007. Glaser, B., and Birk, J. J.: State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in central Amazonia (Terra Preta de Indio). *Geochimica et Cosmochimica Acta* 82, 39 – 51, <https://doi.org/10.1016/j.gca.2010.11.029>, 2011. Gebhardt, A.: ‘Dark Earth’: Some results in rescue archaeological context in France. In: Macphail, R.I., Acott, T. (Eds). *Bulletin 1 of the archaeological soil micromorphology working group University of Greenwich*, Greenwich, 45 – 47 pp., 1997. Gehrt, E., Geschwind, M., Schmidt, M. W. I.: Neolithic, fire and chernozem - or: What does the ceramist have to do with the blacks? *Archäologisches Korrespondenzblatt*, 32, 21 – 30, DOI: 10.1016/j.geoderma.2007.01.009, 2002. Golchin, A. J. A., Baldock, P. Clarke, T. Higashi, and Oades, J. M.: The effects of vegetation and burning on the chemical composition of soil organic matter in a volcanic ash soil as shown by ^{13}C NMR spectroscopy. II. Density fractions. *Geoderma*, 76, 175 – 192, [https://doi.org/10.1016/S0016-7061\(96\)00103-6](https://doi.org/10.1016/S0016-7061(96)00103-6), 1997. Hecht, S. B.: Indigenous soil management and the creation of Amazonian Dark Earths: Implications of the Kayapó practices. In: Lehmann, J., Kern, D.C., Glaser, B., Woods W.I. (Eds). *Amazonian Dark Earths: Origin, properties, management*, Kluwer Academic Publishers, Dordrecht, 355 – 372 pp., 2003. Hirst, K. K.: Mesolithic period: Complex hunter-gatherers in Eurasia, <https://www.thoughtco.com/mesolithic-life-in-europe-before-farming-171668>, lastaccess 7 February 2019, 2017. Howard, J.: *Anthropogenic soils*. Springer International, Cham- Switzerland, 2017. Hollesen, J., Jensen, J. B., Matthiesen, H., Elberling, B., Lange, H., and Meldgaard, M.: The future preservation of a permanently frozen kitchen midden in Western Greenland. *Conservation and Management of Archaeological Sites*, 14, 159 – 168, <https://doi.org/10.1179/135050312Z.00000000013>, 2013. Hollesen, J., Callanan, M., Dawson, T., Fenger-Nielsen, R., Friesen, T. M., Jensen, A. M., Markham, A., Martens, V. V., Pitulko, V. V., and Rockman, M.: Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity* 92, 573 – 586, 2018. Kämpf, N., and Kern, D. C.: O solo como registro da ocupação humana pré-histórica na Amazônia. In: *Tópicos em Ciência do solo*.1 ed. Viçosa. Sociedade Brasileira de Ciência do Solo 6, 277 – 320, 2005. Kawa, N. C., and Oyuela-Caycedo, A.: Amazonian Dark Earth: A model of sustainable Agriculture of the past and future? *The International Journal of Environmental, Cultural, Economic, and Social Sustainability*, 4, 9 – 16, DOI: <https://doi.org/10.18848/1832-2077/CGP/v04i03/54453>, 2008. Kern, D. C.: Caracterização pedológica de solos com terra arqueológica na região de Oriximiná- PA. Porto Alegre. MSc Thesis. Soils Department, Universidade Federal do Rio Grande do Sul, Brazil, 1988. Kern, D.C.: Geoquímica e Pedogeocímica de sítios arqueológicos com Terra Preta na Floresta Nacional de Caxiuanã (Portel-Pará). Doctoral Thesis, Center for Geosciences, Federal University of Pará, Belém, 1996. Lehmann, J., Kern, Silva, J.P., Steiner, C., Nehls, T., Zech, W., and Glaser, B.: Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure, and charcoal amendments. *Plant and Soil*, 249, 343 – 357, 2003a. Lehmann, J., Kern, D.C. Glaser, B., and Woods, W.I.: Amazonian Dark Earths: Origin, properties, management. Kluwer Academic Publishers, Dordrecht, 2003b. Lima, H. N.: Gênese, química, mineralogia e micromorfologia de solos da Amazônia Ocidental. Tese de doutorado. Universidade Federal de Viçosa, Brazil, 2001. Macphail, R. I.: The micromorphology of dark earth from Gloucester, London, and Norwich: an analysis of urban anthropogenic deposits from the Late Ro-

sia, <https://www.thoughtco.com/mesolithic-life-in-europe-before-farming-171668>, lastaccess 7 February 2019, 2017. Howard, J.: *Anthropogenic soils*. Springer International, Cham- Switzerland, 2017. Hollesen, J., Jensen, J. B., Matthiesen, H., Elberling, B., Lange, H., and Meldgaard, M.: The future preservation of a permanently frozen kitchen midden in Western Greenland. *Conservation and Management of Archaeological Sites*, 14, 159 – 168, <https://doi.org/10.1179/135050312Z.00000000013>, 2013. Hollesen, J., Callanan, M., Dawson, T., Fenger-Nielsen, R., Friesen, T. M., Jensen, A. M., Markham, A., Martens, V. V., Pitulko, V. V., and Rockman, M.: Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity* 92, 573 – 586, 2018. Kämpf, N., and Kern, D. C.: O solo como registro da ocupação humana pré-histórica na Amazônia. In: *Tópicos em Ciência do solo*.1 ed. Viçosa. Sociedade Brasileira de Ciência do Solo 6, 277 – 320, 2005. Kawa, N. C., and Oyuela-Caycedo, A.: Amazonian Dark Earth: A model of sustainable Agriculture of the past and future? *The International Journal of Environmental, Cultural, Economic, and Social Sustainability*, 4, 9 – 16, DOI: <https://doi.org/10.18848/1832-2077/CGP/v04i03/54453>, 2008. Kern, D. C.: Caracterização pedológica de solos com terra arqueológica na região de Oriximiná- PA. Porto Alegre. MSc Thesis. Soils Department, Universidade Federal do Rio Grande do Sul, Brazil, 1988. Kern, D.C.: Geoquímica e Pedogeocímica de sítios arqueológicos com Terra Preta na Floresta Nacional de Caxiuanã (Portel-Pará). Doctoral Thesis, Center for Geosciences, Federal University of Pará, Belém, 1996. Lehmann, J., Kern, Silva, J.P., Steiner, C., Nehls, T., Zech, W., and Glaser, B.: Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure, and charcoal amendments. *Plant and Soil*, 249, 343 – 357, 2003a. Lehmann, J., Kern, D.C. Glaser, B., and Woods, W.I.: Amazonian Dark Earths: Origin, properties, management. Kluwer Academic Publishers, Dordrecht, 2003b. Lima, H. N.: Gênese, química, mineralogia e micromorfologia de solos da Amazônia Ocidental. Tese de doutorado. Universidade Federal de Viçosa, Brazil, 2001. Macphail, R. I.: The micromorphology of dark earth from Gloucester, London, and Norwich: an analysis of urban anthropogenic deposits from the Late Ro-

man to Early Medieval periods in England. In: Bullock, P., Murphy, C.P. (Eds). *Soil micromorphology*, A B Academic Publishers, Berkhamsted, U.K. pp. 245 – 252, 1983. Macphail, R. I.: Reconstructing past land use from dark earth: examples from England and France. In: Lorans, E., Rodier, X. (Eds). *Archéologie de l'Espace Urbain*. Coédition CTHS Presses Universitaires François Rabelais, Tours, pp. 251 – 261, 2014. Macphail, R.I., Crowther, J., and Cruise, G.M.: Microstratigraphy. In: Bateman, N., Cowan C., Wroeâ€œBrown R., (Eds). *London's Roman amphitheatre: Guildhall Yard*, City of London, Museum of London Archaeology Service, London, pp. 160 – 164, 2008. Macphail, R.I., Galinie, H., and Verhaeghe, F.: A future for Dark Earth. *Antiquity* 77, 349 – 358, 2003. Malavolta, E.: *Manual de Química Agrícola - Nutrição de Plantas e Fertilidade do Solo*. Edit. Agronomica Ceres Ltda., São Paulo, 1976. McDonagh, S.: Art on the rocks: Dating ancient paintings in the caves of Borneo. *Science*, 164, 147 – 148, 2003. McMichael, C.H., Palace, M.W., Bush, M.B., Braswell, B., Hagen, S., Neves, E.G., Silman, M.R., Tamanaha, E.K., and Czarnecki, C. Predicting pre-Columbian anthropogenic soils in Amazonia. *Proc. Royal Soc. B* 281, 20132475, 2014. Migliavacca, M., Pizzeghello, D., Ertani, A., and Nardi, S.: Chemical analyses of Archaeological sediments identified the ancient activity areas of an Iron Age building at Rotzo (Vicenza, Italy). *Quat. Int.* 289, 101 – 112, DOI: 10.1016/j.quaint.2012.07.016, 2013. Mücher, H., Sevink, J., Berkamp, G., and Jongmans, J.: A pedological and micromorphological study of Mediterranean loessial deposits near Gerona, NE-Spain. *Quat. Int.*, 5, 9 – 22, [https://doi.org/10.1016/1040-6182\(90\)90021-U](https://doi.org/10.1016/1040-6182(90)90021-U), 1990. Nicosia, C., Devos, Y., and Borderie, Q.: The contribution of geosciences to the study of European dark earths: a review. *Post-Classical Archaeologies*, 3, 145 – 170, 2013. Nicosia, C., and Devos, Y.: Urban dark earth. In: Smith, C. (Eds). *Encyclopedia of Global Archaeology*. Springer, New York, 2014. Nicosia, C., Devos, Y., and Macphail, R. I.: European Dark Earth. In: Nicosia, C., Stoops G. (Eds). *Archaeological soils and sediments micromorphology*. John Wiley & Sons, pp. 331 – 343, 2017. Nicosia, C., Langohr, R., Mees, F., Arnoldus-Huyzendveld, A., Bruttini, J., and Cantini, F.: Medieval Dark Earth in an active alluvial setting from the Uffizi Gallery complex in Florence, Italy. *Geoar-*

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chaeol., 27, 105 – 122, <https://doi.org/10.1002/gea.21403>, 2012. Novotny, E., Hayes, M. H. B., Madari, B.E., Bonagamba, T. J., Deazevedo, E. R., de Souza, A. A., Song, G., Nogueira, C. M., and Mandrich, A. S.: Lessons from the Terra preta de Indios of the Amazon Region for the Utilization of Charcoal for Soil Amendment. *Brazilian Chemical Society*, 20, 1003 – 1010, DOI: 10.1590/S0103-50532009000600002, 2009. Parnell, J. B.: Soil chemical analysis of activity areas in the archaeological site of Piedras Negras, Guatemala. Master's Thesis. Brigham Young University, USA, 2001. Pettry, D. E., and Bense, J. A.: Anthropic epipedons in the Tombigee Valley of Mississippi. *Soil Sci. Soc. Am. J.*, 53, 505 – 511, <https://doi.org/10.2136/sssaj1989.03615995005300020034x>, 1989. Peverill, K. I., Sparrow, L. A., and Reuter, D. J.: Soil analysis. An interpretation manual. CSIRO Publishing, Collingwood, 1999. Richter, D. D.: Humanity's transformation of Earth's soil. *Soil Sci.*, 172, 957 – 967, DOI: 10.1097/SS.0b013e3181586bb7, 2007. Ricigliano, K.: *Terra Pretas: Charcoal amendments influence on relict soils and modern Agriculture*. *Journal of Natural Resources and Life Sciences Education*, 40, 69 – 72, 2011. Runge, E. C. A.: Soil development sequences and energy models. *Soil sci.*, 115, 183 – 193, 1973. Schmidt, M. J., and Heckenberger, M. J.: Amerindian Anthrosols: Amazonian Dark Earth formation in the upper Xingu. In: Woods, W. I., Teixeira, W.G., Lehmann, J., Steiner, C., WinklerPrins, A., Rebellato, L. (Eds). *Amazonian Dark Earths: Wim Sombroek's Vision* Springer, Berlin. 163 – 191 pp., 2009. Schmidt, M. J., Skjemstad, J.O. and Jäger, C.: Carbon isotope geochemistry and nanomorphology of soil black carbon: Black chernozemic soils in central Europe originate from ancient biomass burning. *Global Biogeochemical Cycles* 16, 1123, 2002. Schaefer, C. E. G. R., Lima, H. N., Gilkes, R. J., and Mello, J. W. V.: Micromorphology and electron Microprobe analysis of phosphorus and potassium forms of an Indian Black Earth (IBE) Anthrosol from Western Amazonia. *Australian Journal of Soil Research* 42, 401 – 409, 2004. Sheil, D., Basuki, I., German, L., Kuyper, T.W., Limberg, G., Puri, R.K., Sellato, B., Van Noordwijk, M., and Wollenberg, E.: Do Anthropogenic Dark Earths occur in the interior of Borneo? Some initial observations from East Kalimantan. *Forests* 3, 207 – 229, 2012. Šmejda, L., Hejcmam, M., Horak, J., and Shai, I.:

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Ancient activities as important sources of nutrients (P, K, S, Zn, and Cu) in Eastern Mediterranean ecosystems- The case of biblical Tel Burna, Israel. *Catena* 156, 62–73, <https://doi.org/10.1016/j.catena.2017.03.024>, 2017. Šmejda L., Hejcman M., Horák J., and Shai I.: Multi-element mapping of anthropogenically modified soils and sediments at the Bronze to Iron Ages site of Tel Burna in the southern Levant. *Quat. Int.*, 483, 111 – 123, <https://doi.org/10.1016/j.quaint.2017.11.005>, 2018. Smith, N. J. H.: Anthrosols and human carrying capacity in Amazonia. *Ann. Am. Assoc. Geogr.*, 70, 553 – 566, <https://doi.org/10.1111/j.1467-8306.1980.tb01332.x>, 1980. Smith, N. J. H.: The Amazon River forest: a natural history of plants, animals, and people. Oxford University Press, New York, 1999. Soil Survey Staff.: Illustrated guide to soil taxonomy. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska, 2015. Solomon, D., Lehmann, J., Fraser, J. A., Leach, M., Amanor, K., Frausin, V., Kristiansen, S. M., Millimouno, D., and Fairhead, J. Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative. *Front. Ecol. Environ.*, 14, 71 – 76, 2016. Sombroek, W.: Amazon soils. A reconnaissance of the soils of the Brazilian Amazon region. Pudoc, Wageningen, 1966. Souza, L. C., Lima, H. V., Rodrigues, S., Kern, D.C., Silva, A. P., and Piccinin, J. L.: Chemical and physical properties of an anthropogenic dark earth soil from Braganca, Para, Eastern Amazon. *Acta Amazonica*, 46, 337 – 344, 2016. Stoops, Ge., Stoops, Gu., Laleman, M. C.: Micromorphological study of the black layer of Gent. Abstracts of the International Working Meeting on Micropedology, Gent, 90 p., 2001. Tenenbaum, D. J.: Carbon Mitigation from the Ground Up. *Environmental Health Perspectives* 111, 70 – 73, 2009. van Smeerdijk, D. G., Spek, T., Kooistra, M. J.: Anthropogenic soil formation and agricultural history of the open fields of Valthe (Drenthe, the Netherlands) in medieval and early modern times. *Mededelingen Rijks Geologische Dienst*, 52, 451 – 479, 1995. Wiedner, K., Schneewei, J., Dippold, M.A., and Glaser, B.: Anthropogenic Dark Earth in Northern Germany-The Nordic analogue to Terra preta de Índio in Amazonia. *Catena* 132, 114 – 125, <https://doi.org/10.1016/j.catena.2014.10.024>, 2015. Winkler-Prins, A., and Falcão, N.: Soil fertility management and its contribution to the formation

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of Amazonian dark earths in urban homegardens, Santarém, Pará, Brazil. 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane, Australia, 2010. WinklerPrins, A.: Terra Preta: The mysterious soils of the Amazon. Environmental Studies, Advanced Academic Programs, Washington D.C, 2014. Woods, W. I., Teixeira, W. G., Lehmann, J., Steiner, C., WinklerPrins, A. M. G. A., and Rebellato, L.: Amazonian Dark Earths: Wim Sombroek's Vision. Springer, Dordrecht, 2009. Whitehead, N. L., Heckenberger, M. J., and Simon, G.: Materializing the past among the Lokono (Arawak) of the Berbice River, Guyana. *Antropológica.*, 114, 87 – 127, 2010. World Reference Base (WRB): FAO Soils Portal. <http://www.fao.org/soils-portal/data-hub/soil-classification/world-reference-base/en/>, last access: 25 October 2020. 2015.

Interactive comment on SOIL Discuss., <https://doi.org/10.5194/soil-2020-51>, 2020.

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