Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative

Dawit Solomon[1]*, Johannes Lehmann[1], James A Fraser[2], Melissa Leach[3], Kojo Amanor[4], Victoria Frausin[2], Søren M Kristiansen[5], Dominique Millimouno[6], and James Fairhead[7]

We describe for the first time a current indigenous soil management system in West Africa, in which targeted waste deposition transforms highly weathered, nutrient- and carbon-poor tropical soils into enduringly fertile, carbon-rich black soils, hereafter "African Dark Earths" (AfDE). In comparisons between AfDE and adjacent soils (AS), AfDE store 200–300% more organic carbon and contain 2–26 times greater pyrogenic carbon (PyC). PyC persists much longer in soil as compared with other types of organic carbon, making it important for long-term carbon storage and soil fertility. In contrast with the nutrient-poor and strongly acidic (pH 4.3–5.3) AS, AfDE exhibit slightly acidic (pH 5.6–6.4) conditions ideal for plant growth, 1.4–3.6 times greater cation exchange capacity, and 1.3–2.2 and 5–270 times more plant-available nitrogen and phosphorus, respectively. Anthropological investigations reveal that AfDE make a disproportionately large contribution (24%) to total farm household income despite its limited spatial extent. Radiocarbon (^{14}C) aging of PyC indicates the recent development of these soils (115–692 years before present). AfDE provide a model for improving the fertility of highly degraded soils in an environmentally and socially appropriate way, in resource-poor and food-insecure regions of the world. The method is also "climate-smart", as these soils sequester carbon and enhance the climate-change mitigation potential of carbon-poor tropical soils.

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Despite some improvement in environmental outcomes, conventional agriculture continues to contribute to biodiversity loss, climate change, and the degradation of terrestrial and freshwater systems (Foley *et al.* 2011). A major global challenge is to develop sustainable, "climate-smart" agricultural systems that feed growing populations and adapt to climate change while maintaining lower carbon footprints and staying within critical ecological thresholds (Lal 2010; FAO 2011). Nowhere are these challenges greater than in sub-Saharan Africa (SSA), where agriculture supports the livelihoods of 750 million people and where average grain yields are the lowest of any region in the world (Conway and Toenniessen 2003). Most smallholder farmers in SSA practice low-input subsistence agriculture and face a wide array of biophysical and climate-related production constraints. To increase agriculture production and food security – while also contributing to climate-change mitigation – innovative, climate-smart soil-management practices must be developed to improve soil fertility. At present, such sustainable agricultural management strategies and models are largely lacking.

One widely proposed approach is to recreate conditions that led to the formation of Amazonian Dark Earths (ADE), a legacy of pre-Columbian indigenous people in South America that has no known current analogs (Glaser and Birk 2012). Recorded use of these soils dates as far back as 5000 years before present (BP), with the majority forming between 1000–2000 years BP (Whitehead *et al.* 2010), yet they still aid in the sustainable intensification of smallholder agriculture. However, it remains unclear whether ADE were created deliberately for agriculture, or were merely a byproduct of settlement patterns and associated domestic activity; it is also uncertain whether it would be appropriate to replicate the use of such soils in contemporary Africa. In this multidisciplinary exploration in SSA, we examine the existence of indigenous soil enrichment practices capable of improving the fertility and carbon-storage capacity of highly degraded soils, and consider the potential that such anthropogenic soils have for mitigating climate change, improving livelihoods, and fostering resilience in the local population.

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[1]*Soil and Crop Sciences Section, School of Integrative Plant Sciences, Cornell University, Ithaca, NY* *(ds278@cornell.edu); [2]*Lancaster Environment Centre, Lancaster University, Lancaster, UK;* [3]*Institute of Development Studies, University of Sussex, Brighton, UK;* [4]*Institute of African Studies, University of Ghana, Legon, Ghana;* [5]*Department of Geoscience, Aarhus University, Aarhus, Denmark;* [6]*Cabinet Universitaire de Recherches-Actions, Kissidougou, Republic of Guinea;* [7]*Department of Anthropology, University of Sussex, Brighton, UK*

Methods

Study site description and soil analysis

Preliminary participatory surveys revealed African Dark Earth (AfDE) candidates at 150 sites in 93 localities in northwest Liberia, and at 27 sites in 17 villages in Ghana. We conducted the study in 2011, at six sites in northwest Liberia (Borkeza, Delema, Dadazu, Gbokolomie, Memene, and Wenwuta) and at five sites in Ghana (two in the Ashanti region [Ekyeniso and Bonfa Dadamu] and three in the Brong-Ahafo region [Asante Kwa, Sabule, and Sogliboi]) (WebTable 1). The Liberian sites range from 209–475 m above sea level (asl), with a mean annual temperature of about 26°C, and mean precipitation of about 2900 mm yr^{-1}. The soils of the area are well drained, deep yellowish-red to red, sandy loam to sandy-clay-loam-textured soils classified as Oxisols or Ultisols (WebTable 1). The Ghanaian sites range from 184–315 m asl, with a mean annual temperature of about 27°C, and a mean precipitation of about 1090–1480 mm yr^{-1}. The soils from the Ashanti region are well-drained, yellowish-red to deep red, friable sandy-loam-textured Ultisols, while the soils from Brong-Ahafo are deep red in color and are dominated by sandy-loam-textured Oxisols. To investigate the formation and agroecological importance of the dark earths, we compared AfDE with adjacent soils (AS), which, due to their similarity to the underlying mineralogy, provide a valid proxy for the "original" soils from which AfDE developed (Figure 1; WebTable 1). AfDE and AS samples were obtained from deep (up to 2.6 m) soil profiles positioned at <100-m intervals. For a more comprehensive description of experimental methodology, please refer to WebPanel 1.

Environmental anthropology research methods

To understand local knowledge of AfDE, land cover typology, and associated land use, we combined qualitative and quantitative methods from environmental anthropology (Bernard 2011) in northwest Liberia and Ghana. These methods include: (1) participant observation (eg taking part in daily domestic and agrarian activities), (2) open interviews where conversations were directed to particular topics of interest, (3) oral and site histories involving evidence-gathering with elders and community leaders, and (4) transect walks with local farmers while discussing key landscape features (WebPanel 2).

Household food consumption and market survey

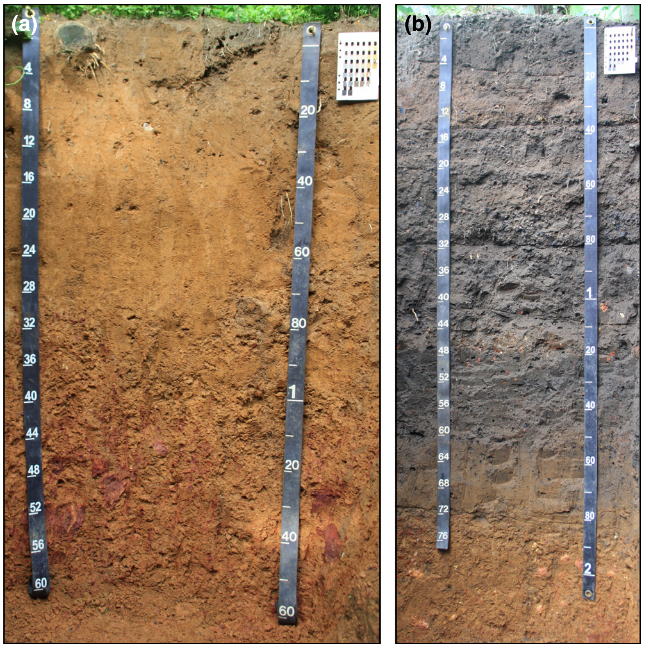

Figure 1. *Representative pictures of yellowish-red AS (a) and dark colored AfDE (b) soil profiles collected from the village of Wenwuta in Liberia. The AS profile and the AfDE profile were obtained by digging soil pits (3 m × 2 m × 1.6 m and 3 m × 2 m × 2.4 m, respectively), both of which extended to the parent material layer. The depth of AfDE and accumulation of pyrogenic carbon (PyC) in these black earths extend to a depth of 1.80 m.*

To investigate the extent to which crops grown in AfDE and AS contribute to household diet, we conducted a 6-month-long, longitudinal survey of household food consumption and soil origins of food crops (whether crops were grown in AfDE [ie in the 3-ha area covered by AfDE around farm field kitchens and palm-oil production sites and current settlements within the purple line in Figure 2] or in AS [ie in a 50-ha area where shifting cultivation is practiced]) within the 1000-ha Wenwuta village territory in northwest Liberia (Figure 2). On two randomly chosen days a week from March to September 2011, we randomly selected 15 households from a subsample of 34 that were willing to participate in research (from a total of 43), visited them after the evening meal, and recorded the identity and associated soil origins of all food items consumed that day (within the past 24 hours, as recalled by the participants). We recorded the parts of each meal (eg rice, greens, palm oil, and meat) separately, each as one "food item".

We also calculated the contribution of food crops produced in AfDE and AS to household incomes with an 18-month longitudinal market survey of the same village. Once a week between February 2011 and May 2012, we recorded produce sold by all 34 participating households at the weekly market in Zolowo, a town near Wenwuta. We visited every household before market, and noted the quantity and price of each product that they were sending to market, as well as the soil in which they were produced.

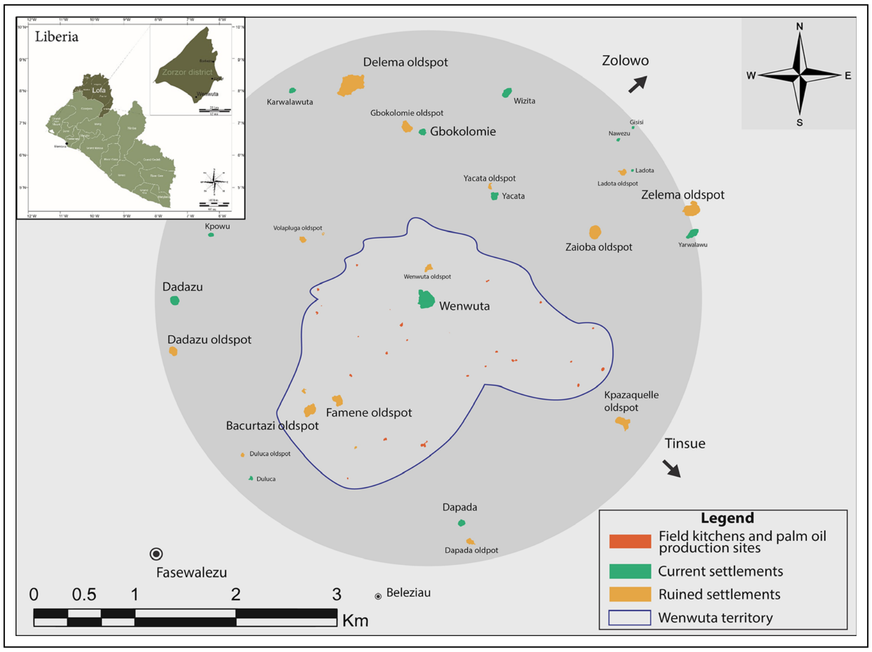

Figure 2. *Distribution of AfDE within a 3-km radius (2827 ha) of the village of Wenwuta in Zorzor district, Lofa County, Liberia. The inset map of Liberia shows our in-depth field sites in Zorzor district in Lofa County, highlighted in dark green.*

Participatory GPS mapping

To measure the distribution of the various types of AfDE over the landscape, we asked members of local communities who possessed specific knowledge of different areas of the landscape to map what they perceived to be the outer edges of AfDE sites by walking around them using a handheld GPS unit (Figure 2).

Results and discussion

We uncovered an existing, yet overlooked soil management system that has long been – and continues to be – an important feature of the indigenous West African agricultural repertoire. It transforms highly weathered, infertile, yellowish-to-red tropical soils (Oxisols and Ultisols) into black, highly fertile, carbon-rich soils (Figure 1). We combined social anthropology and soil-science methods to examine the agricultural and ecological importance of these AfDE in Liberia and Ghana (WebTable 1).

In all regions surveyed, farmers identified areas of anthropogenically enriched dark soils that are highly prized and part of the local nomenclature (WebTable 2). Anthropological research conducted in Wenwuta village in northwest Liberia (Figure 2) revealed three types of dark earths, based on their occurrence in the landscape: (1) AfDE around field kitchens and palm-oil production sites (average size 0.1–0.5 ha), (2) AfDE encircling current settlements (average size 0.5–2 ha), and (3) AfDE surrounding abandoned settlements (average size 0.5–14 ha). Participatory GPS mapping of AfDE of the area within a 3-km radius of Wenwuta (Figure 2) showed that these soils cover 29 ha, or about 1% of the 2827 ha surveyed. Within the 29 ha, proportions of AfDE documented by type were as follows: around field kitchens and palm-oil production sites (7%), encircling current settlements (29%), and surrounding abandoned settlements (64%).

AfDE, which are frequently used to cultivate diverse crops planted in the multistory home gardens, are important in helping to ensure household food security. The most common species grown in AfDE include plantain (*Musa* × *paradisiaca*), cassava (*Manihot esculenta*), and taro (*Colocasia esculenta*). A survey of household consumption of food products grown in the AfDE present around field kitchens and palm-oil production sites and current settlements in Wenwuta (the area within the purple line in Figure 2) showed that these small patches of AfDE, covering just 3 ha, supplied 26% of food items consumed (WebFigure 1). The rest was produced from 50 ha of AS – the "original" soils from which AfDE developed (Figure 1) – cleared and farmed yearly under shifting cultivation, mainly of rice (*Oryza* spp), along with intercrops of beans (*Vigna* spp) and other species (WebFigure 1). Crops grown in AfDE in Wenwuta made up 24% of farm household income during the 18-month survey of the origins of crops sold at the market (WebFigure 2). These qualities of AfDE are appreciated by members of the local community and are expressed in the following quote: "Anything that you can plant in the red soil…can grow well in the black soil, but plantain, banana, and cocoa will not grow well in the red soil. The black soil is the chief of all soil around here!"

As for the beneficial characteristics of AfDE, evidence from soil analyses corroborates observations made by the local community. AfDE are moderately to slightly acidic (pH = 5.6–6.4) as compared with AS, which are very strongly to strongly acidic (pH = 4.3–5.3; WebFigures 3 and 4); less acidic soil conditions reduce aluminum toxicity and increase the availability of critical plant nutrients. Phosphorus and nitrogen availability in AfDE are 5–270 and 1.3–2.2 times greater than in AS, respectively (Figure 3). Likewise, concentrations of calcium, magnesium, and potassium are 2–37, 1–20, and 1–4 times greater in AfDE than in AS, respectively (WebFigure 5). Cation exchange capacity, which reflects the soil's ability to retain plant-available nutrients, is 1.4–3.6 times higher in AfDE than in AS (Figure 4), while bulk density of AfDE (the dry weight of soil per unit volume of soil) is up to 50% lower than in the surrounding AS (WebFigure 6). The unusually high concentrations of available calcium and phosphorus in surface and subsurface layers of AfDE are likely to be due to anthropogenic addition of animal bones, which are typically rich in calcium phosphates (Sato *et al.* 2009; Warren *et al.* 2009; Zwetsloot *et al.* 2015). The combination of char and bones – along with additions of ash with very high acid-neutralizing capacity – raises the pH of the otherwise highly weathered acidic AS. This improves phosphorus availability, either by stimulating the mineralization of organic phosphorus in the soil or through increased solubility of inorganic phosphorus already present (Demeyer *et al.* 2001). The presence of 2–3 times as much total soil nitrogen and available potassium concentrations in surface and subsurface layers of AfDE compared to the original background soil can be explained by additions of various plant and animal residues and ash. The availability of higher concentrations of plant nutrients in AfDE, coupled with the moderate to neutral pH in surface and subsurface layers, is important for supporting the highly diversified multistory homestead cultivation practiced on most AfDE in West Africa.

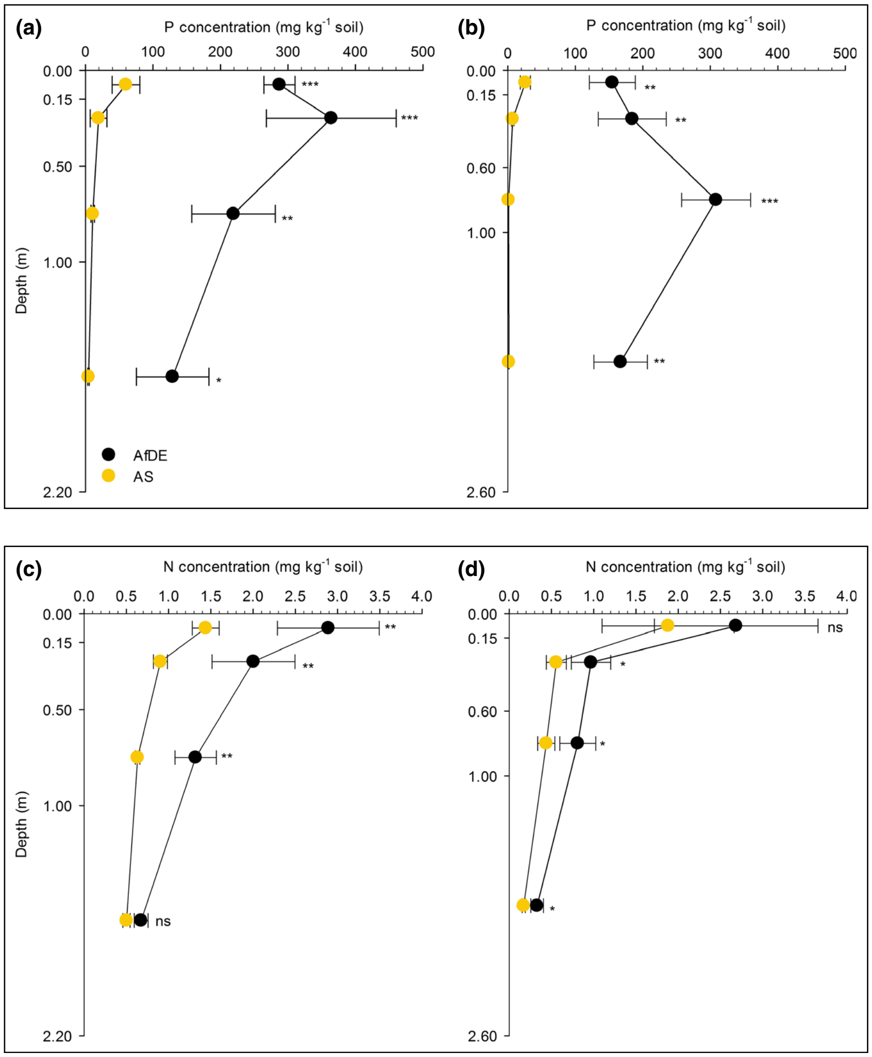

Figure 3. *Phosphorus and nitrogen concentrations in deep soil profiles of AfDE and AS from Liberia (a and c, respectively) and Ghana (b and d, respectively). AfDE contain significantly higher concentrations of available phosphorus (a and b) and total nitrogen (c and d) in the surface and subsurface layers of AfDE than in AS. Error bars show standard error of the mean. ***, **, and * indicate significant differences at $P \leq 0.001$, $P \leq 0.01$, and $P \leq 0.05$, respectively.*

The TOC stocks stored in AfDE to a depth of ~2.0 m are generally 2–3 times as large as those in AS (Figure 5), with 2–26 times greater levels of PyC in the surface layer alone (WebTable 3). PyC is a carbonaceous residue of fires or charring that mineralizes more slowly than other forms of organic carbon; it has a projected half-life of hundreds to thousands of years longer than uncharred plant biomass residues, enabling long-term soil carbon storage even in hot and humid tropical ecosystems where organic matter typically decomposes rapidly (Solomon *et al.* 2007; Lehmann *et al.* 2008). Soils rich in PyC therefore act as long-term carbon sinks, supporting climate-change mitigation efforts (Glaser and Birk 2012). PyC is also largely responsible for the significantly higher nutrient retention and cation exchange capacity observed in AfDE as compared with the surrounding soils (Figure 4c; WebFigure 7; Liang *et al.* 2006).

Local farmers have a thorough understanding of the soil management practices that transform AS to AfDE, and of the dark soils' characteristic fertility. Interviewees in Liberia and Ghana described how AfDE form through additions of several types of waste: ash and char residues from cooking; byproducts from processing palm oil and producing homemade soap; animal-based organic inputs such as bones from food preparation; and harvest residues and plant-biomass-based domestic refuse such as palm thatch, palm-fruit heads, and rice straw. These continuous, high-intensity nutrient and carbon depositions lead to an ongoing formation of highly fertile and carbon-rich AfDE in and around settlements (similar to that shown in Figure 1). Local people in Liberia frequently describe these AfDE-forming practices as anthropogenic; one local, for

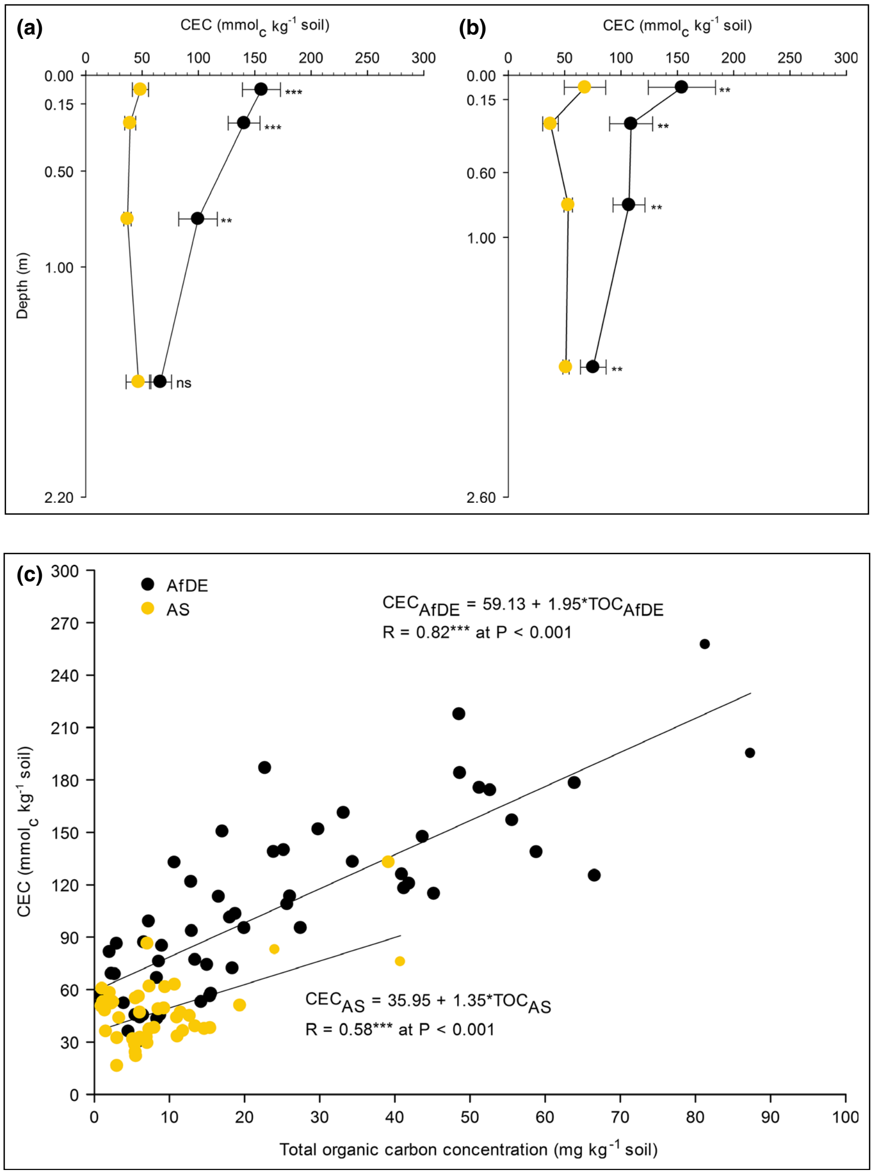

Figure 4. *Cation exchange capacity (CEC) in deep soil profiles of AfDE and AS from Liberia (a) and Ghana (b), and the relationship between CEC and soil organic carbon (c) in AfDE and AS. The linear relationship between CEC and soil organic carbon (c) was calculated by combining data from Liberian and Ghanaian sites. Panels (a) and (b) show that AfDE contain significantly higher cation retention and CEC in the surface and subsurface layers of AfDE than in AS. Error bars show standard error of the mean. ***, **, and * indicate significant differences at* $P \leq 0.001$, $P \leq 0.01$, *and* $P \leq 0.05$, *respectively, whereas "ns" indicates that the difference is not statistically significant at* $P \leq 0.05$.

example, said, "God made the soil, but we put the dirt there and made it fertile."

Oral histories and radiocarbon (^{14}C) dating confirmed that the indigenous soil management practice that creates AfDE is ancient and has continued in a similar manner up to the present day. Gayflor Zee Pewee, an 81-year-old chief at Wenwuta, described a connection between AfDE depth and settlement age: "The black soil was not here [when people arrived to settle] but when they put the town down, the dirt they threw started forming black soil…If you dig a hole you can see how far down the black soil goes, and this shows how old the town is."

Radiocarbon analyses of char particles collected from deeper soil profiles (0.5–1.8 m) in six AfDE sites – identified by the local communities in Liberia and Ghana as old settlements – support this observation, as ages were found to lie between 115 and 692 years BP (WebTable 4). On the other hand, the soil fertility, agroecological, and farmland carbon-storage benefits of AfDE were achieved relatively recently and continue today, in contrast to ADE in South America, which date as far back as 5000 BP, with the majority forming between 1000–2000 years BP (Whitehead *et al.* 2010).

Conclusions

Our identification and characterization of AfDE provides evidence that an indigenous sustainable soil management system in West Africa can transform infertile and carbon-poor, humid tropical soils into long-lasting, fertile, carbon-rich, and productive soils capable of supporting intensive farming in an ecologically and socially sustainable manner. This transformation is similar to the well-documented anthropogenic formation of ADE in Amazonia. Whereas in South America the activities that lead to the creation of these anthropogenic soils were largely disrupted after European conquest (Erickson 2003), we show that the formation of analogous AfDE is ongoing in West Africa. This indigenous soil management practice provides a basis for understanding AfDE formation elsewhere in Africa. More importantly, it is a climate-smart foundation for agricultural innovation attuned with SSA farming practices in ways that could improve sustainable production on agricultural land, enhance the livelihoods of smallholder farmers, and promote resilience to climate change in this chronically food-insecure region. Although our investigation examines AfDE presence and use in Liberia and Ghana, further comparative research will be necessary to

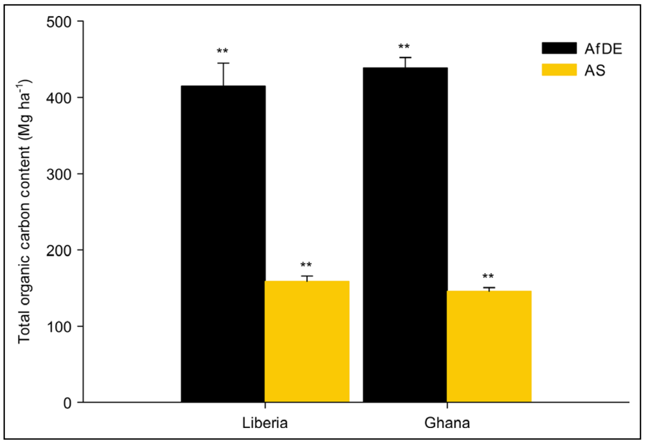

Figure 5. *Total organic carbon stock in deep soil profiles of AS and AfDE from Liberia (down to 2.2 m) and Ghana (down to 2.6 m). The depth of AS and AfDE profiles extend from the surface horizon to the parent material layer, as shown in Figure 1. Error bars show standard error of the mean. ** indicates significant differences at* $P \leq 0.01$.

determine the conditions (soil, agroecological, and social) under which the benefits of these soils can be realized, as well as to determine the limitations in applying this soil management system in other geographic contexts.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1226/suppinfo