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Charcoal Whirlwinds and Post-Fire Observations in Serengeti National Park Savannahs

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Abstract

Whirlwinds and visible dust devils occur over semi-arid ecosystems and entrain particles from the ground surface. Fires produce abundant charcoal across savannahs and the resulting blackened surfaces create a large albedo contrast. Whirlwinds have been observed associated with active fires; yet, there are few published observations on post-fire landscapes. Spatiotemporal patterns of whirlwinds have been documented for a limited number of regions and have not been made for the ecosystems of eastern Africa. From field-based sightings in the Serengeti National Park, Tanzania, we report on whirlwinds over burned savannah patches that entrained large quantities of charcoal to produce black coloured charcoal devils that lofted charcoal into the atmosphere. Two occurrences of charcoal devils were sighted and photographed, one each in the Western Corridor (Bunda District) and Lamai (Serengeti District), Mara Region. The observations were compared with regional scale meteorological data and remote sensing satellite imagery and albedo estimates of the land cover conditions. Although direct meteorological or particulate matter measurements were not made, the observations show that both charcoal devils differed in colour, funnel shape, height, and savannah land cover types (different woody to grass fuel canopies), and thus different charcoal morphologies. Charcoal laden whirlwinds require further study and characterization to analyse the contribution to local-scale redistribution of matter and regional-to-global fluxes of terrestrially derived atmospheric particulates. Future research focusing on the spatiotemporal patterns of whirlwinds over burned patches of savannah, the formation, duration and dissipation mechanisms, and characterisation of the entrained material would contribute to our understanding of the phenomena. The redistribution of organic and clastic material would contribute to understanding of detrital fluxes to depositional environments, such as lakes, wetlands, and snow.

Keywords: Atmospheric boundary layer; Convection; Detritus; Dust devils; Fires; Particulate matter.

Introduction

Whirlwinds are a common occurrence in semi-arid and arid ecosystems (Balme and Greeley 2006, Lorenz et al. 2016) that persist from tens of seconds to hours (Lorenz 2013) and are a local aeolian erosion process that form visible dust devils by the suspension of surficial materials into the atmosphere (Raack 2014, Onishchenko et al. 2019). Dust devils form across tropical savannahs during warm daytime conditions when there is high convection during the dry seasons, which is the same time for peak fire conditions. The semi-arid Serengeti ecosystem receives bimodal annual rainfall with two drier seasons, usually between January to February and June to September (Sinclair and Norton-Griffiths 1979). Fine particles of charcoal at sizes from <10 μm up to several centimetres are common to tropical forest and grassland soils and abundant on the soil surface across large expanses of relatively flat or hilly land during and after savannah fires. Charcoal is produced from the incomplete combustion of biomass in savannah and wooded ecosystems. Both grass-sourced and wood-sourced charcoal with a jet black colour, a variety of morphologies, and variable lustre are produced amongst other combustion byproducts, such as white ash and grey ash. Grass charcoal tends to be thinner and has a longer major axis and is sent aloft with moderate convection and advection as the particles are more prone to atmospheric entrainment from the surface by post-fire surface winds than wood charcoal. Wood-sourced charcoal tends to be blockier in shape and is usually only entrained up into the atmosphere during intense pyrogenic convection in large and hot forest fires (Umbanhowar and McGrath 1998, Pisaric 2002, Vachula et al. 2021). Charcoal devils are whirlwinds with a high proportion of black charcoal as the entrained material from the surface, similar to documented dust devils, ash devils, leaf devils, coal devils, and hay devils (specific to agricultural fields).

Immediately after a fire, much of the charcoal remains in the local-to-extralocal area of the burn (Whitlock and Millspaugh 1996, Peters and Higuera 2007, Higuera et al. 2007) and is transported to local depositional environments to accumulate in sediments and soils (Whitlock and Larsen 2001). Both wind and surface water transport charcoal to depositional environments during a fire and through post-fire erosion (Whitlock et al. 1997, Conedera et al. 2009). Recent burns are the primary sources of charcoal and secondary sources of transportable charcoal that comes from the stock stored within eroding soils (Gavin 2001, Whitlock and Larsen 2001, Lertzman et al. 2002). Some quantity of charcoal is transported long distances by wind (Clark 1988, Adolf et al. 2018, Vachula and Richter 2018, Vachula 2021) and has been directly observed in temperate forest fires (Pisaric 2002, Tinner et al. 2006). Charcoal preserves well in depositional environments, such as lake and wetland sediments, because it is abundant and relatively inert (Scott 2010, Scott and Damblon 2010, Hawthorne et al. 2018). Charcoal analysed from the sediments of depositional environments are a useful proxy for past fire activity over geologic time and utilised to analyse ecological changes (Whitlock and Larsen 2001, Whitlock et al. 2010), human-environment interactions (Taylor et al. 2005, Bowman et al. 2011, Archibald et al. 2012, Petek 2018, Shipton et al. 2018) and rangeland management (Marchant 2021, Dabengwa et al. 2022). Subfossil charcoal records derived from sediments have been used to study the past fire ecologies of savannahs and land use changes (Ekblom and Gillson 2010, Ekblom et al. 2011, Leys et al. 2015, Githumbi et al. 2018a).

Here we report on field-based observations of an earth surface process that has few documented observations in the literature and that may be an important component of charcoal transport mechanisms from the surface of burned savannah ecosystems into the atmosphere and then to adjacent highlands and depositional basins. We then present some literature particular to dust devils, globally and in eastern Africa, as context to discuss potential for transport mechanisms of charcoal over long distances to other depositional environments and the relative contribution to background charcoal accumulation rates, and thus, for the interpretation of regional paleoenvironmental records. We present potential future research directions to characterise the entrained loads in charcoal whirlwinds and to quantify the detrital component through the use of existing methods, such as dust and pollen traps, to better understand transport and deposition of charcoal.

Materials and Methods

This paper presents *ad hoc* observations made during fieldwork campaigns in the savannahs of northern Tanzania during July and August 2016 (Figure 1). The observers sighted the formation, movement and dissipation of two dust devils across large, recently burned areas of savannah in Serengeti National Park. These dust devils over burned savannah appeared loaded with charcoal fragments and other detritus that produced dust devils with a characteristic black colouration. The colour was markedly blacker than the soil dust colour, including black cotton soils that also produce darker dust devils. On each of the two occurrences, the observers sighted and took photographs of a charcoal laden dust devil (Figure 2), and each occurrence most likely also contained an amount of organic matter and clastic dust. The photographs captured different whirlwind morphologies, heights, aspect ratio, and colours, as well as the landscape and vegetation where the dust devils traversed.

Both nearby meteorological measurements and satellite imagery for 2016 were obtained to characterise the weather and land cover conditions at the time of observing the charcoal-laden whirlwind on the post-fire landscape of the Western Corridor, Serengeti National Park. Visible light satellite imagery (TIFF format) with detected active fires (red squares) acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) of the Western Corridor area were downloaded for June–September 2016 to visualise the dry season and fire activity progression (Figure 3A–D). Temperature and relative humidity weather data were downloaded from the Musoma Meteorological Station (WMO station ID 63733) for the year 2016 (precipitation was not available). Monthly total precipitation was supplied from a rain gauge station at Speke Bay Lodge (Coordinates –2.266896, 33.796418, ~1140 m asl) near the Ndabaka Gate, Western Corridor.

Albedo values were queried from the MCD43A3 V6 Albedo Model dataset across several pixels of burned areas and adjacent unburned areas in the Western Corridor for the MODIS image dated 25 August 2016 at 08:10 h GMT (11:10 h local time, Figure 3C), the day when one charcoal whirlwind was observed (Figure 2, left panel). Albedo is a non-dimensional unitless quantity that ranges between 0 (black, all light is absorbed) and 1 (white, all light reflected). Pixels from burned areas had albedo values between 0.058 and 0.099 and unburned areas varied between 0.137 and 0.158. This spatial contrast could promote different potential for localised convection above burned patches as more radiation is absorbed by the burned land surface, and could entrain charcoal, organic detritus, and minerogenic dust from the burned surfaces.

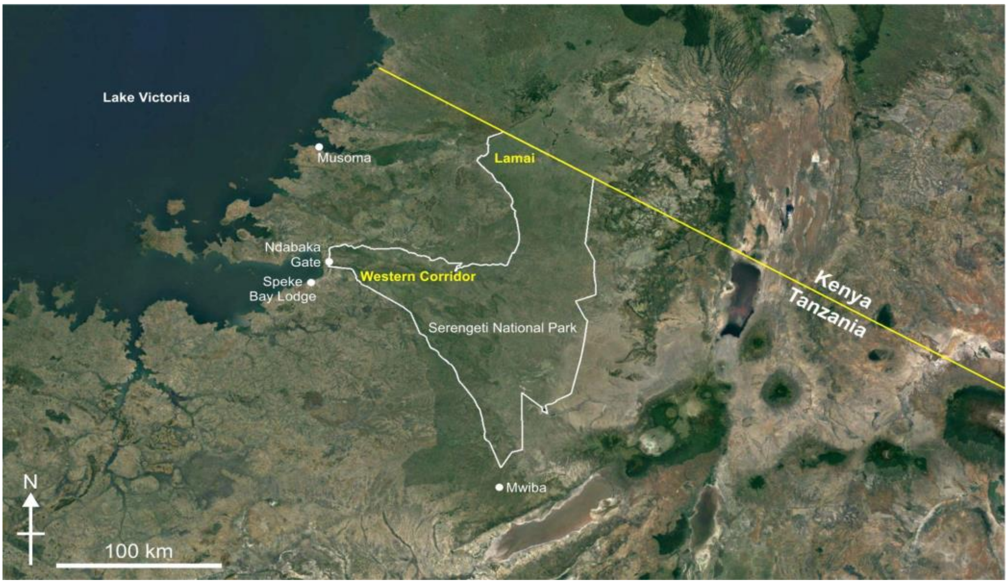

Figure 1: Map showing the study area. Locations mentioned in the text (white font), Serengeti National Park (white outline, Source: UNEP-WCMC and IUCN 2022) and the two regions where dust devils with high charcoal loads were observed during fieldwork (yellow font). Meteorological data were available from stations at Musoma (Meteorological Station GSOD ID 637330-99999, WMO ID 63733; location –1.500, 33.800; 1147 m asl) and Speke Bay Lodge (privately operated; location –2.267, 33.796; ~1140 m asl). Basemap imagery has been adapted from Google Earth, 2022. http://earth.google.com/web/ (multiple imagery acquisition dates in mosaic).

Figure 2: Whirlwinds observed that were directly over recently burned areas of savannah in Serengeti National Park, Tanzania, that appeared to contain abundant charcoal and probably an amount of other dry grass fragments and clastic dust. On the left, a recent fire burned the grass and scorched the trees in the midground of the photograph that provided very abundant charcoal into the whirlwind in the Western Corridor (Figure 1). The photograph was dated 25 August 2016 (Julian day 238) during the afternoon (daily temperature range = 18.6–26.5 °C, mean = 22.7 °C, mean relative humidity = 55.8%, daily precipitation = 0 mm). On the right, a large burned area of continuous grass provided charcoal into a lofty whirlwind, near Lamai, northern Serengeti near the Kenya border (Figure 1). The photograph was acquired on 17 July 2016 (Julian day 199) at 12:50:38 local time with a Nikon D3000 digital camera (Daily temperature range = 21.2–27.2 °C, mean = 23.5 °C, mean relative humidity = 63.8%, precipitation = 0 mm). Refer to Figure 3 for meteorological conditions.

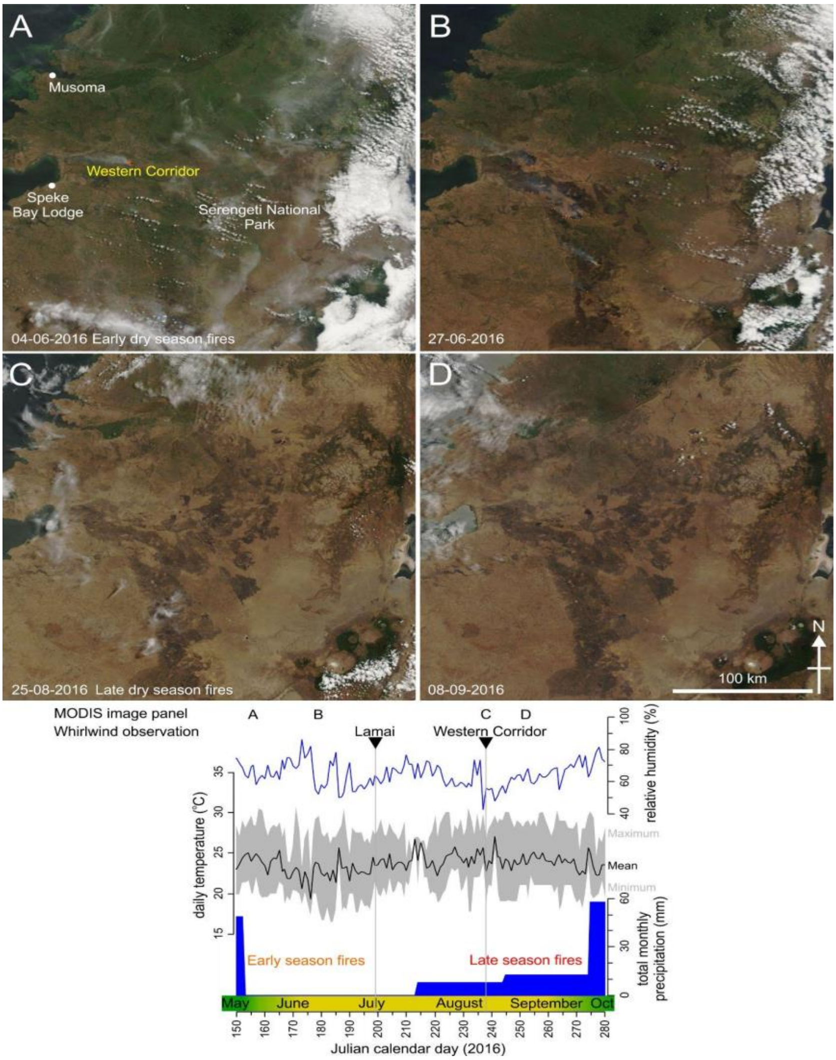

Figure 3: MODIS satellite images acquired from two dates prior (**A**, **B**) to the observation of the charcoal-laden whirlwind (black triangle symbol) in the Western Corridor (**C**, and left panel of Figure 2). Panel **A** shows green grass areas and drier savannah at the beginning of the dry season with some early fires (red squares) and smoke plumes in the Western Corridor. Note the presence of smoke plumes, being blown to the west, emanating from early dry season fires. Panel **B** shows continued drying of savannahs and more burned area in the Western Corridor and southwestern Serengeti. Panel **C** shows the vast burned areas throughout the ecosystem on the day of the charcoal-laden whirlwind observation in the Western Corridor (Julian day 238, 25-08-2016). Panel **D** shows the dry and burned area conditions prior to the onset of October rains. Meteorological stations are shown (white circles) and weather data for the 2016 dry season are shown below. Daily mean relative humidity and daily maximum, minimum, and mean temperatures were obtained from Musoma Meteorological Station and total monthly precipitation from a rain gauge at Speke Bay Lodge. Note that 2016 was a leap year for Julian calendar dates. DD-MM-YYYY date format. MODIS images have been obtained using NASA Worldview Snapshots under the open Data and Information Policy. Musoma Meteorological Station data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD).

Results and Discussion

Serengeti whirlwinds with charcoal loads

The two observed whirlwinds with very high loads of charcoal were observed on recently burned savannahs within days of each fire. The charcoal devils did not appear to be driven by convection from active flames, with no visible evidence of firebrands and there was limited smoke from smouldering areas. The whirlwinds appeared to be more laden with blackened grass-sourced charcoal and are different to (whiter and greyer) ash devils, which have been reported in previous publications (Idso 1974) or related to smoke and convection from active fires (Miethe 1899, Lorenz et al. 2016). The photographs capture the sighting of the phenomenon and evidence to some of the variability of whirlwind shapes, landscapes and vegetation types on the surface where they were viewed. As the photographs were taken anecdotal to other activities, no other observations were made on the characteristics of the dust devils themselves, the entrained dust particles, or the meteorological or topographical conditions. The photographs document the occurrence of grassy charcoal laden dust devils over recently burned savannah. The entrainment of large quantities of charcoal contributes to the black appearance to the whirlwinds (Giersch and Raasch 2021) and potentially lifts charcoal and black carbon aerosols higher into the atmosphere and clouds (Rushingabigwi et al. 2018). This may be an important component of the organic and minerogenic matter flux to highlands, which burn less frequently than savannahs (Hempson et al. 2018, Beale et al. 2018, Probert et al. 2019), and more distant depositional basins, such as Lake Victoria (Temoltzin-Loranca et al. 2022).

Although there is high spatiotemporal complexity for weather conditions across the Serengeti plains and western highlands, we use the Musoma and Speke Bay Lodge meteorological data as general indicators of concomitant conditions. Both charcoal-laden whirlwinds were observed during sunny partly cloudy conditions of the dry season with average relative humidity <65% at Musoma and mean daily temperature of >22 °C (Figure 3).

Dust devil literature related to fire

Several reviews of dust devil research are presented in the literature (Balme and Greeley 2006, Horton et al. 2016, Lorenz et al. 2016). Lorenz et al. (2016) discuss some fire-related whirlwinds and few studies focus on the organic matter component within the dust devils themselves. Charcoal laden dust devils over post-fire patches of burned savannah will have been observed in the past but have not been documented in the literature reviewed by the authors. Ash laden dust devils were observed and described from human ignited peat fires in Germany during the 1800s (Lorenz et al. 2016); but it is unclear if these were observed during the active burns or if these dust devils formed over the post-fire burned areas. Few scholarly publications focus on dust devils in eastern Africa and evidence is anecdotal or related to other research, such as vulture use of convective air (Pennycuick 1973). Pennycuick (1972) described airborne observations of a dust devil over an active savannah fire near Seronera, Serengeti, that carried smoke as high as the daytime cloud base. It is not explicit from the published notes if the convection related to active fires or solely from the radiation effects on the burned patch of savannah and if black charcoal was entrained. For comparison to dust devils unrelated to fire activity in eastern Africa, see an anecdotal colour photograph of a small dust devil over barren soil in Tanzania (Knippertz 2017, see Figure 9 therein) and a black-and-white photograph of a minerogenic dust devil in Shombole, Kenya (Pennycuick 1972). A census of dust devil development, in space and time across semi-arid and arid regions, such as those observations reported in Arizona, USA (Sinclair 1969), would be useful for understanding the entrainment and transport of dust and to map out regions that may have a higher contribution to dust and also charcoal flux to the atmosphere. Fieldwork that focuses on spatial and temporal patterns of dust devils and characterisation of the conditions and whirlwind itself are relatively rare because of the ephemeral tendency of the phenomena (Tang et al. 2018). Potentially, certain savannah areas are more prone to the development of charcoal-laden whirlwinds and the export of charcoal particles into the atmosphere and could be a target for further field-based research.

Fire and aeolian entrainable and transportable material

Fires generate readily erodible materials that include organic (burned and unburned) and clastic detritus because topsoil stability is reduced and through exposure to the atmosphere (Figure 4). In some cases, soil crusts may impede minerogenic entrainment into the atmosphere (Vos et al. 2020) and pyrogenic crusts could potentially separate entrainment of organic detritus, including charcoal and dry grass fragments, and minerogenic particles. The relative importance of topography, weather, surface conditions, and charcoal particle sizes should be investigated, as well as the possible interacting effects from long lasting smouldering heat. Many dust models use an indication of the quantity of erodible particles (clay and silt) and assume that this does not change through time (Woodruff and Siddoway 1965, Hagen 1991, Fryrear et al. 1998). However, after a fire, there is a near instantaneous large amount of erodible materials, especially organic detritus (Figure 4B and 4C). Albedo differences between the blackened area of charcoal over savannah burns and surrounding landscape (Figure 4A, 4D and 4E) may promote localised convection patterns and contribute to whirlwind formation (Horton et al. 2016), which requires further study to adequately characterise. The organic detrital load of terrestrial dust devils remains one component of uncertainty for comparative analyses among dust devils in different environments as well as for comparisons to other planets, such as Mars (Balme and Greeley 2006).

The morphology, density and mass of grass leaf and stem charcoal (Umbanhowar and McGrath 1998, Courtney Mustaphi et al. 2014; Figure 4B) likely contributes to increased entrainment and lift. Grey and white ash produced by nearly complete combustion is common for woody detritus and trees near the ground surface that smoulder after ignition for many hours in hot and dry air (Figure 4A and 4C). Anecdotally, in November 2018, single fragments of grass charcoal up to 10 cm in length have been observed to be transported from active savannah fires 10 km from the Western Corridor within Serengeti National Park to the shore of Speke Gulf, Lake Victoria. The mechanisms and quantity of lowland and lower montane charcoal transported and accumulated into depositional environments on the isolated mountains of Kenya and Tanzania (Courtney Mustaphi et al. 2021a, Githumbi et al. 2021a) or the sediments of very large lakes, such as Lake Victoria (Temoltzin-Loranca et al. 2022), over long timescales will be of interest for the interpretation of palaeoenvironmental data. Examination of charred grass cuticles in sedimentary records and comparisons between highland and lowland grassy vegetation could be investigated to analyse the spatial sources of charcoal (Wooller et al. 2000, Ficken et al. 2002, Wooller 2002). The fire weather and convection patterns for lofting charcoal particles into the atmosphere have not been explored and remain an emerging topic for study. Charcoal analysis of dust and pollen traps (Ohlson and Tryterud 2000) across savannah and upslope elevations would contribute to our understanding of lowland-highland contributions of charcoal, which has been demonstrated for pollen studies (Markgraf 1980, Schüler et al. 2014). Our review of the literature found no publications that examined the detrital organic content of dust traps, charcoal or uncharred biomass, and it remains a potential knowledge gap to be addressed in future research of atmospheric particulates. Commonly used samplers include the Modified Wilson and Cook (MWAC) and the Big Spring Number Eight (BSNE) (Mendez et al. 2016) among others (Courtney-Mustaphi et al. 2014a, Courtney-Mustaphi et al. 2014b, Brahney et al. 2020), which could be used to examine detrital organic particulates from post-fire landscapes and experimentally in the laboratory or the field. Characterization of aeolian transported inorganic and organic detritus could be done to investigate the relative contribution of aeolian transported dust and charcoal found in the study of deposits in lakes (Nelson et al. 2012, Courtney Mustaphi and Pisaric 2014, Courtney Mustaphi and Pisaric 2018, Courtney Mustaphi et al. 2021a), wetlands (Gillson 2006, Ekblom and Gillson 2010, Leys et al. 2017, Githumbi et al., 2021a), and other accumulations (Shipton et al. 2018, Li et al. 2020, Williamson and Menounos 2021).

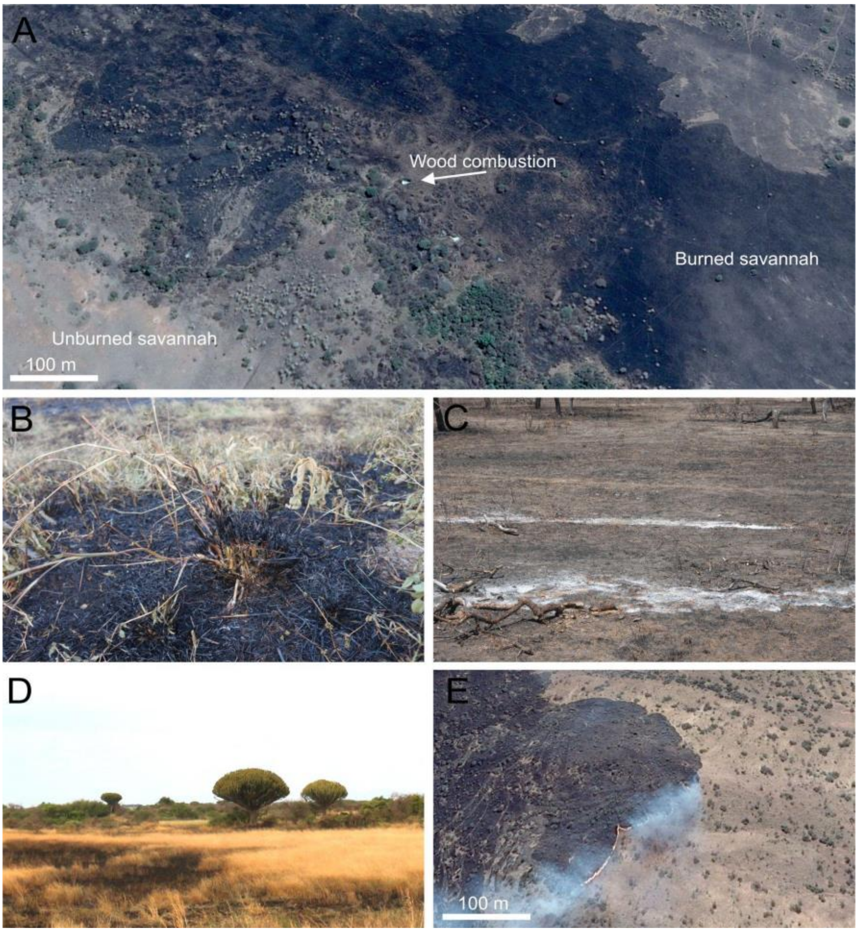

Figure 4: Burned savannah areas of the Greater Serengeti Ecosystem, Tanzania. **A**; Shows burned and unburned savannah across the southwestern area of the Western Corridor (Figure 1). Note the white ash outlines produced from nearly complete combustion of trees relative to the quicker combustion of leaf and stem of the surrounding grasses (see Figure 4C). Imagery date acquired on 9 August 2016, centred on –2.241071, 34.008950, 1177 m asl (Google Earth 2022), during the late fire season and shows a relatively complete burn with limited patchiness of unburned grass coverage within the active fire area. **B**; Recently burned savannah with grass leaf charcoal and the surviving fire-resistant grass crown near Ndabaka Gate, 12 July 2018. **C**; White ash outline produced from nearly complete combustion of a knocked over tree bole in Mwiba, southern Serengeti, ~1670 m asl (Figure 1). **D**; Patchy savannah burn to illustrate potential albedo differences between burned and unburned patches, Ndabaka Gate, 12 July 2018, during the early to mid dry season. Active savannah fire front and smoke during the late dry season, Western Corridor, 21 July 2017, centred on –2.259094, 34.318262, 1365 m asl (Google Earth 2022).

Deposition of charcoal and detritus into the fossil record

The long term spatial and temporal dynamics of charcoal from source-to-sink contributes to the empirical variable background rate of charcoal accumulation in geological records, such as lacustrine (Nelson et al. 2012, Colombaroli et al. 2014, Colombaroli et al. 2018), palustrine (Githumbi et al. 2018b, 2021a and 2021b), or marine sediments, as well as to snow and glacial ice on Mt. Kilimanjaro (Thompson et al. 2002, Gabrielli et al. 2014). Charcoal accumulation is also quantified and interpreted in depositional settings of archaeological study, for example, Panga ya Saidi cave deposits in Kenya had an increase in charcoal throughout the Middle Stone Age (Shipton et al. 2018). The varying background rate of charcoal accumulation into sediments is often used as a general indicator of past plant biomass abundance and increased fire occurrence in palaeovegetation and paleofire studies (Long et al. 1998, Marlon et al. 2006, Higuera et al. 2009). Charcoal entrainment, transport and deposition in the atmosphere and by surface water have yet to be characterised for any of the fire-prone ecosystems of tropical eastern Africa. The contribution of charcoal derived from fires in lowland areas to depositional environments in highland areas, including Kilimanjaro and Eastern Arc Mountains, was identified as an uncertainty that was not disentangled from local catchment fires (Schüler et al. 2012, Finch et al. 2017, Courtney Mustaphi et al. 2021a, Courtney Mustaphi et al. 2021b, Githumbi et al. 2021a). The taphonomic effects of various aeolian and water flow mechanisms could produce preferentially sorted charcoal morphotype assemblages (Scott et al. 2000), which have yet to be fully explored. Comparisons of source material (soil surface charcoal and clastic particles) with pollen and dust traps, as well as sediment core data would begin to yield data to differentiate various source areas and transport mechanisms and enhance the interpretation of sedimentary charcoal records and reconstructed fire histories.

Conclusions

Whirlwinds that entrain and transport dust and organic materials from the surface form visible devils that are a common occurrence sighted over relatively flat or hilly landscapes during the dry season when dust-sized particles are readily entrained. The high albedo contrasts and the abundance and entrainment potential of charcoal over recently burned areas can result in dust devils with very high charcoal loads. The sighting and photography of dust devils with entrained charcoal loads over recently burned savannahs in Serengeti National Park show that there is potential for whirlwinds to mobilise materials from post-fire surfaces and the combination of meteorological and remote sensing information demonstrates the potential for further research into this understudied phenomenon. The spatiotemporal occurrences of post-fire whirlwinds are uncertain and have yet to be the focus of research. Future research at local, regional and global scales will help to quantify whirlwinds as a transport mechanism that erodes organic and inorganic material from burned areas to other parts of the ecosystem, with implications for geochemical cycling, pollution, atmospheric chemistry, air quality, and matter fluxes. Future research will also have to differentiate between pyrogenic convection, smouldering and smoke heating of the atmosphere, and albedo difference contributions to whirlwind formation, quality, dissipation and matter fluxes. Charcoal laden dust devils may occur in other ecosystems other than savannahs, and it is unclear what the contribution is to ecology and air quality, as well as to the interpretation of paleoenvironmental records from geoarchives and archaeological contexts. The amount of charcoal flux from savannahs to depositional areas across the region, such as Lake Victoria (Temoltzin-Loranca et al. 2022), the Indian Ocean, and glacial ice on Mt. Kilimanjaro over geologic timescales remains difficult to disentangle from palaeoecological records (Courtney Mustaphi et al. 2018).

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Competing Interest

The authors of this paper declare that there are no competing interests.

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