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The East African contribution to the formalisation of the soil catena concept

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ABSTRACT

The concept of the soil catena was first explicitly formalised by Geoffrey Milne and his colleagues in East Africa in the 1930s. It has been widely adopted and applied in soil survey and continues to be of great value in soil and other field sciences The concept characterises widespread patterns in which distinctive associations of soils and vegetation are consistently located in specific slope positions. The formalisation of the concept in an area well outside the mainstream of soil research appears to have been due to the combination of highly visible recurrent patterns of red slope soils overlooking dark valley clays in East Africa's extensive savannahs, together with a group of receptive and collaborative soil scientists working in a supportive institutional environment. The concept is often attributed to Geoffrey Milne, the group's coordinator, but we show that several colleagues and friends also contributed. We summarise some of the early soil catenas characterised by Milne and his colleagues in Uganda, Kenya and Tanganyika Territory (now Tanzania). Even at the beginning, it was appreciated that the catena was not universally applicable and that heterogeneity of parent materials can override catenary patterns. The catena was quickly and widely adopted in soil science, and this diffusion has led to some broadening of the definition, and several types of soil pattern are now designated as catenas. The concept has also spread beyond soil science and is used by ecologists, geomorphologists and hydrologists amongst others. It continues to be a paradigm of great explicative and educational power in soil science and ecology.

1. Introduction

Few concepts have proved more useful in tropical soil science than the soil catena, as formalised in the 1930s by Geoffrey Milne and his colleagues in East Africa. Spatial associations between soils and topographic position have long been recognised intuitively by farmers, land managers, and also by the early pioneers in modern soil survey and pedology. The explicit formalisation of these relationships in the soil 'catena' (= chain in Latin; plural strictly *catenae* but more commonly 'catenas) clarified many aspects of the spatial distribution of soils in savannahs and other biomes. We trace the origins and early applications of the concept in East Africa, and outline some of the inevitable broadening in its definition that followed from its global diffusion.

2. Precursors of the catena

In some indigenous systems of land assessment, topographic position is rated above soil *sensu stricto* (Krasilnikov and Tabor, 2003). Even where soils predominate, topography is often an important criterion, and it figures prominently in about half of the 62 ethno-pedological classification systems reviewed by Barrera-Bassols and Zinck (2003). The ethno-pedotaxonomy of the Sukuma people of north-western Tanzania incorporates topographic position (Morison and Wright, 1952; Peat and Prentice, 1949).

The importance of topographic associations was recognised in early studies of East African soils. The visually striking patterns of red soils on slopes over black cracking clays in valleys were identified by agricultural scientists and extension workers in German East Africa, especially Vageler. They noted associations of soil colour, drainage and base status with topographic position during the early years of the 20th century (Phillips, 1929).

Topographic position has been taken as an indicator of soil change and used as an aid to mapping since the beginnings of modern soil survey (Bonsteel et al., 1906; Hall and Russell, 1911).

3. Overview and definition of the catena concept

The term catena *sensu stricto* (Young, 1976) is used for a sequence of distinct but pedogenically related soils that are consistently located on specific facets down a slope, giving recurrent topographically associated soil patterns (Milne, 1936b; 1947). Visible features in most catenas in the East African savannahs include: freely drained, reddish soils

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(a) Upper slope

(b) Valley

Fig. 1. Main soils of low relief catena, Embu, Kenya: (a) Red fine loam on upper slope; (b) Dark clay loam on lower slope. (Photos by S. H. Hallett).

on long, gentle upper and middle slopes; imperfectly drained, dull coloured soils with variegated mottling and blackish ferrimanganiferous concretions on gently concave lower slopes; and dark poorly drained soils in the valleys (Fig. 1). Textural patterns vary considerably but the valley soils are often heavy smectitic clays with higher pH values and base saturations than the red soils upslope. Catena interfluves vary from wide and smooth with deep reddish soils to steep and rocky with shallow greyish soils. The different soils down a catena are associated with floristically and structurally distinct types of vegetation and land management characteristics.

The most widely accessible early definition was by Milne (1947); "*A regular repetition of soil profiles in association with a certain topography*" and that *"a distinctive word is needed in referring to this phenomenon*" and he proposed "*catena"*.

4. Context of the formalisation of the catena concept in East Africa

The formalisation and naming of the concept arose out of the work of a group of East African soil specialists in the 1930s. A feature of their working environment was the freedom to collaborate across territorial borders, largely as an outcome of the Imperial Agricultural Research Congress in 1927. Modern soil survey was then still in its infancy, and the British colonial authorities had only just begun to realise its potential value. The conference passed a resolution to strengthen agricultural research through inter-territorial cooperation in the organisation of soil surveys (Ministry of Agriculture and Fisheries, 1928). This authorised collaboration between the Soil Chemists in the East African territories, i.e. Dr W.S. Martin and G. Griffith in Uganda; V.A. Beckley and G.H. Gethin Jones in Kenya; L.W. Raymond in Zanzibar and the yet-to-be appointed Soil Chemist for Tanganyika Territory (Fig. 2). The chemists were involved in agricultural extension and research in their separate territories, but their remits now included liaison on regional soil characterisation and mapping (Milne et al., 1936).

Geoffrey Milne was appointed as the Soil Chemist to the rehabilitated East African Agricultural Research Station at Amani in Tanganyika (Fig. 2) in 1928 (Nature, 1942). The research programme there included *"Surveys: the study of the basic types of East African soils, their characteristics, formation, distribution and verification in relation to climate and other influences. The work to be contributory to and correlated with the projects African soil survey"* (Nowell, 1930). Milne became the coordinator and inspirational leader for regional soil studies in East Africa.

As well as the soil chemists, others who collaborated with Milne in the mapping and conceptual work included his wife Kathleen, a qualified geographer, and two friends, Clement Gillman and Bernard Burtt. Gillman was an engineer on the Tanganyika Railway for about four decades, but he was also a wide-ranging polymath with a geological background and a keen interest in the geomorphology, ecology (Gillman, 1949) and all aspects of the Tanganyikan landscape (Hoyle, 1987). Burtt was a botanist in the Tanganyikan government service and, like Milne and Gillman, he was an observant, widely travelled and collaborative field scientist (Burtt and Welch, 1957).

The first traceable written identification of catenary patterns in East Africa was by W.S. Martin, who observed and reported repeated slope soil sequences as a landscape feature around the Bukalasa Research Station in Central Uganda (Fig. 2) (Brown et al., 2004). In a letter to Milne prior to the first meeting of the soil chemists at Amani he wrote: "*In connection with the distribution of soils found in this rolling type of country that we have in Uganda such as the Bukalasa samples, it is obvious that all profiles may be found in one geological formation that the differences arise through topography, soil, climate, etc."* He also noted that: "*Over large areas of Uganda where local variation in topography were regularly repeated, a given colour on any map finally produced (on any but an impracticably large-scale) would have to be interpreted as indicating the occurrence not of a single soil but of a sequence of soils occurring generally over the area to be worked out on the actual ground in each instance according to topography and other local influences*" (Martin, 1932). In 1932 he collected a set of soil monoliths and exhibited these at the first Soil Chemists meeting in Amani to show the sequence at Bukalasa (Grunwald, 2005). The sequence he identified on the Basement Complex around Bukalasa was later designated as the Buganda catena (Figs. 2 and 3a). It is typical of many East African catenas with a rocky crest, deep reddish soils on the long midslope; and black cracking clay in the valley.

Buwekalu is another extensive catena in Uganda (Figs. 2 and 3b). This is similar to Buganda, but the relief is greater, there are more rock outcrops on the crest and upper slopes, and the soil textures are coarser, particularly on the lower slopes (Radwanski and Ollier, 1959).

The continued relevance of the catena concept in its area of origin is shown by the study of Rehm and Grashey-Jansen (2016) in the Masaka district of Uganda (Fig. 2). The catena they describe is similar to Martin's Buganda for the soils in the valley and on the slopes, although their slope soils appear to have more iron concretions and plinthite. The main difference is that their catena has a broad and gently convex crest with deep reddish loams (Fig. 3c), in contrast to the steep and rocky crest with shallow soils of Martin's Buganda. The difference is probably due to the lower altitude and more subdued relief of their study area compared to Bukalasa. They designated their catena as Buganda, but in Fig. 3c we call it Masaka, to avoid confusion.

Although Milne visited Kenya, Uganda and Zanzibar, his own fieldwork concentrated on Tanganyika. He identified and mapped a number of catenas (at locations 4, 5 and 9 in Fig. 2), the best characterised of which was at the Ukiriguru Research Station in the northwest of the territory (Fig. 4a). He used it as his type catena in a short note in *Nature* on the role of erosion in pedogenesis, and in his suggestions for soil classification and mapping in East Africa (Milne,

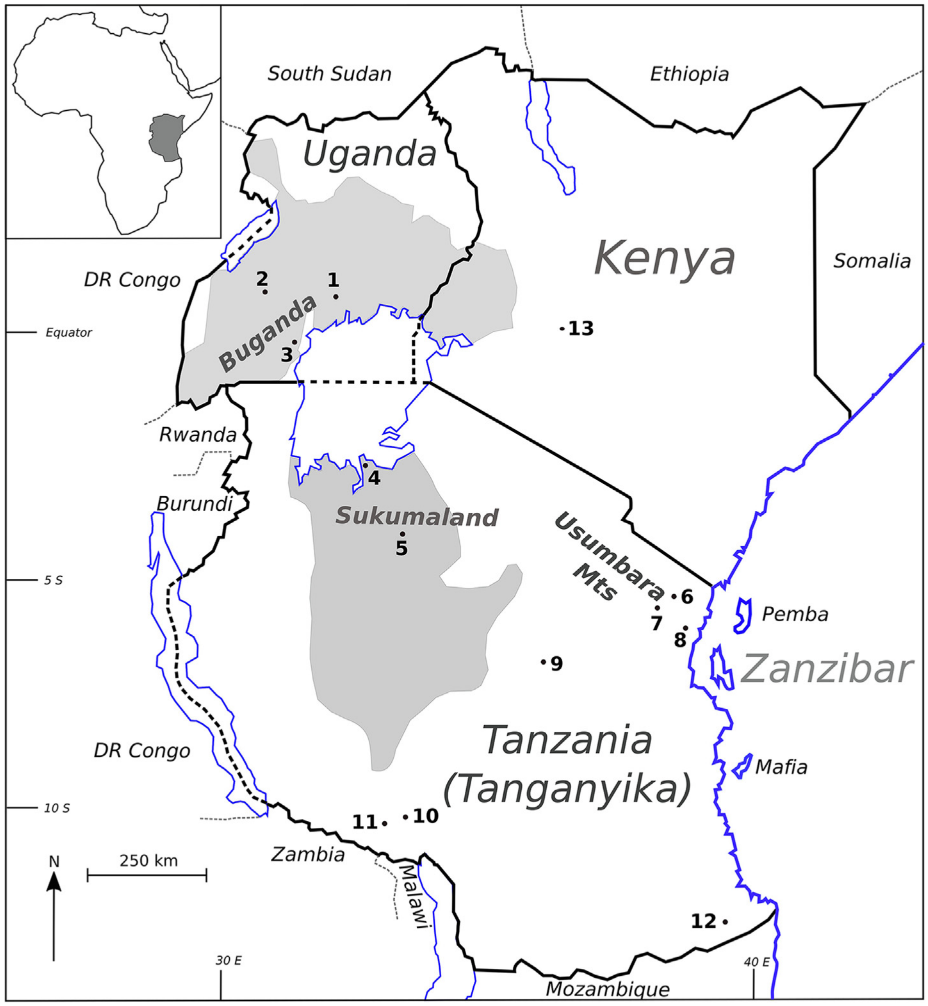

Fig. 2. Soil Association Locations referred to in the text with predominantly catenary soil patterns (shaded) in Provisional Soil Map of East Africa. 1 Bukalasa; 2 Buwekalu; 3 Masaka; 4 Ukiriguru; 5 Unyanyembe; 6 Kitivo; 7 Amani, 8 Muheza; 9 Kongwa; 10 Mbeya; 11 Mbozi; 12 Nachingwea, 13 Embu.

1935b; 1936a).

Although it has a simple topographic profile, this catena is quite complex. Downslope from the shallow stony soils between the tors on the hill crests, the soils on the upper and middle slopes are deep, reddish, leached, and non-calcareous loams of low to moderate nutrient fertility (Peat and Prentice, 1949; Le Mare, 1972; Szilas et al., 2005). Exchangeable base status increases downslope in the greyish soils on the lower slopes, and is considerably higher in the dark valley clays. Another of Milne's (1947) catenas is the Unyanyembe (Fig. 2), which is developed from more siliceous rocks of the Basement Complex, and has coarse textures (Fig. 4b).

The majority of Milne's catenas were in savannah plains with low to moderate relief. He also used the concept in more rugged terrain below the escarpment of the Usumbara Mountains (Milne, 1944). Unlike the transects for relatively undissected slopes in Figs. 3 and 4, he depicted the Usumbara catena in a schematic plan. This enabled him to show localised wash and fan alluvial deposits in dissected parts of the slopes (Fig. 5).

The plan shows that red earths of fairly heavy, though sometimes gritty, textures occupy most of the ridges and their slopes on the undissected slopes. There are dark grey to black clays in the swampy valleys, and a concave intermediate zone of variable width with dull brown to yellow-brown soils, which are sandy at the surface but heavier below and which have a greyish mottled subsoil with some iron concretions. Where the slopes are dissected by low order streams, Milne named most of the young, imperfectly drained and intermittently flooded alluvial soils on the fans as Kitivo (Fig. 4), after a local village (Mugogo et al., 1987).

Milne summarised his territorial findings and conclusions in a government report on a pedo-ecological tour of Tanganyika in 1936 (Milne,1936b). They did not become widely available until published in a comprehensive posthumous paper in the *Journal of Ecology* (Milne, 1947), which was prepared by Gillman.

Milne and his colleagues used catenas when mapping generalised soil patterns over large areas, but they recognised that the concept was not universally applicable. Their provisional soil map of East Africa (Milne et al., 1936) showed catenary patterns as predominant in southern Uganda and northwestern Tanganyika. Although catenas were identified elsewhere, they were not dominant (Fig. 2).

Catenary patterns figured less in early accounts of Kenya's soils, and there is no reference to catenas in Kenya in the text of Soils of East Africa (Milne et al.,1936). However, the map shows predominantly catenary patterns in southwestern Kenya, adjacent to Lake Victoria, and Milne records that *"Mr Gethin Jones has described to me well-marked examples from the formations adjoining the east coast of Lake Victoria"* (Gethin-Jones,1934; Milne, 1935a). V.A. Beckley noted regular patterns of different soils on the long slopes around Mount Kenya (Milne, 1935a), but there are considerable altitudinal and climatic trends within these patterns, and they appear to be climosequences, rather than topographically determined catenas. Fig. 1 shows the soils of an unambiguous Kenyan catena in an area of low-moderate relief to the southeast of Mount Kenya.

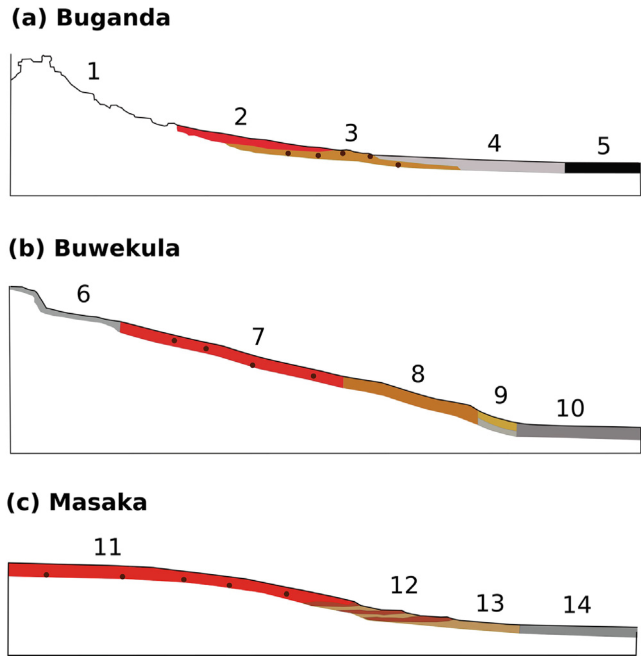

Fig. 3. Schematic transects of Ugandan catenas: (a) Buganda catena (based on Rehm and Grashey-Jansen, 2016): 1 Shallow stony dark grey loam; 2 Deep red earth; 3 Brownish 'clinker' soil, with many Fe concretions; 4 Brownish grey loam; 5 Heavy black clay. (b) Buwekalu catena (based on Radwanski and Ollier,1959): 6 Shallow loamy sand; 7 Deep red sandy clay loam with Fe concretions in subsoil; 8 Deep brown sandy clay loam with Fe concretions in subsoil; 9 Yellowish brown coarse sand with gleyed subsoil; 10 Grey gleyed coarse sand. (c) Masaka catena (based on Rehm and Grashey-Jansen, 2016): 11 Red earth; 12 Red earth with soft Fe concretions; 13 Brownish loam with outcrops of ferricrete; 14 Grey gleyed loam.

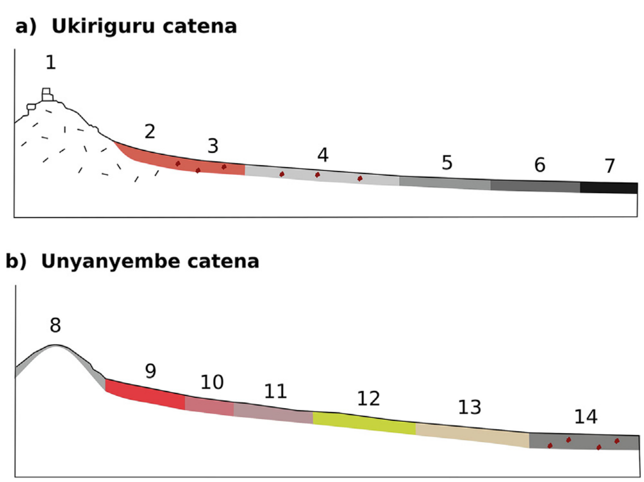

Fig. 4. Schematic transects of Tanganyikan catenas (Based on Milne, 1947): (a) Ukiriguru catena: 1 Granite tors with shallow grey coarse loam; 2 Brownish red loam over granite; 3 Brownish red loam with soft iron concretions; 4 Grey sand with iron concretions; 5 Non-calcareous hard pan soil; 6 Calcareous black sandy clay; 7 Heavy black clay. (b) Unyanyembe catena: 8 stony grey loam & bare rock; 9 Bright red earth; 10 Dull red earth; 11 Slightly reddish grey sand; 12 Yellowish grey sand; 13 Drab sand; 14 Mottled grey sandy clay.

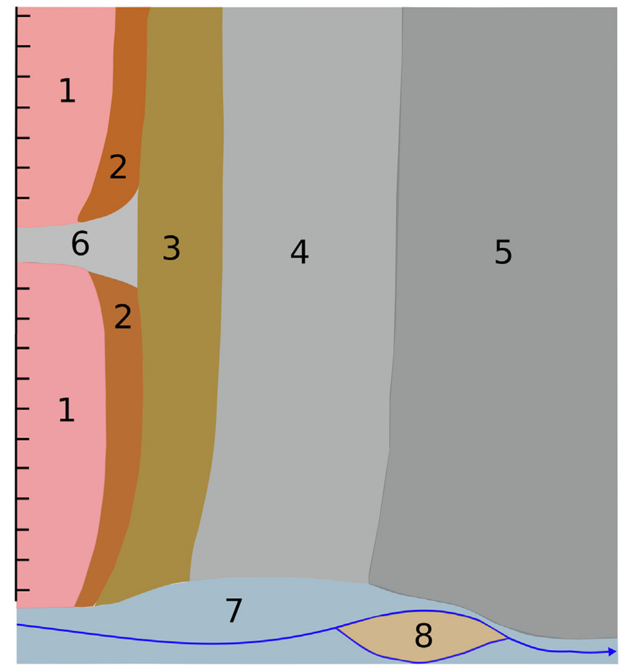

Fig. 5. Schematic plan of Usumbara catena (Based on Milne, 1944): 1 Red earth on upper slope below scarp; 2 Intermediate brown soil on midslope; 3 Hard-setting yellowish brown sandy clay; 4 Greyish black gritty clay; 5 Heavy black clay; 6 Dark greyish clay in wash in minor gully; 7 Imperfectly drained alluvial Kitivo soil; 8 Well drained alluvial soil.

It is clear that Milne himself recognised that catenas are not appropriate in some areas. In what must have been his near-ultimate field trip in Tanganyika, he examined the soils of sisal estates along the Central Railway. He identified 32 soil types and associated them with different landscape positions, but he did not mention catenas. He designates some soils as 'fossil' to indicate that they appear to have developed in old regoliths, and possibly experienced moister paleoclimates than at present. This report is also notable in that his soil suitability classification for sisal includes the forthright "*Class I. Soils too good for sisal*" (Milne, 1941).

5. Post-Milne applications of the catena in East Africa

Post-Milne soil surveyors in Tanganyika/Tanzania were also selective in their application of the catena concept. The 1968–69 survey of Tanzania recognised catenary patterns as predominant only in the northwestern part of the country (Wengell et al., 1969). Brian Anderson described some soil distributions as catenary in his studies at Kongwa and Nachingwea (Fig. 2), but noted that parent materials and landscape history also determined soil patterns (Anderson, 1957; Muir et al., 1957). He later noted that "*The catena was a bit of an oversimplification. Some high ground in Tanzania is a relic of very ancient erosion cycles (mid tertiary?) so the soils are palaeosols, while the valleys are younger, so the conditions are not uniform over wide areas*" (B. Anderson, p.c., 2001). Baker (1970) believed that "*.. no simple catena is evident in most parts of the country, Ukiriguru which provides the classic catena, and the surrounding country being an exception. In general the soils are more closely associated with the underlying rocks or parent material than with any topographic sequence*".

Gordon Anderson (1962) mapped soils around Muheza (Fig. 2), including the Kitivo area, at reconnaissance scale using a mixture of catenary and non-catenary mapping units. At Mbozi in southwestern Tanganyika (Fig. 2), Spurr (1955) designated some soil patterns as catenary. He attributed them partly to differences in the age of soil parent materials in areas where lower younger erosion surfaces in the valleys have encroached on to, and stripped off the deep and intensively weathered regolith of the older Jurassic interfluves.

Although catenary patterns were not shown as predominant in Zanzibar on the 1936 map, the reddish soils of western Zanzibar were later described as catenary (Calton et al., 1955). However, the concept is less applicable elsewhere on the island, as lithological differences

Table 1
Glossary of topographically related soil patterns.

Toposequence	Consistent sequence of soils on specific land facets downslope. Toposequence in which the soils are pedogenically linked, often by downslope transfers of material
Compound catena	Catena in which the topographic differentiation of soils is partly due a consistent sequence of different parent materials downslope
Transformational catena	Catena in which the topographic differentiation of soils is mainly due to a consistent pattern of different weathering and leaching regimes downslope
Translocational catena	Catena in which the topographic differentiation of soils is due to the lateral transfer of water, solutes and solids downslope, usually by surface runoff subsurface throughflow, soil creep or mass movement
Recurrent landscape pattern	Topographically recurrent soil pattern. Similar to toposequence
Hydrosequence	Catena in which the topographic differentiation of soils is due to the lateral transfer of water downslope, giving consistent pattern of different weathering and leaching regimes. Similar to transformational catena
Association	Hydrosequence used as a composite soil mapping unit by the Soil Survey of Scotland to encompass patterns of soils with different topgraphically-related drainage regimes on similar parent materials. (NB 'Association' is used as a mapping unit by the Soil Survey of England and Wales for soils with similar morphologies and drainage regimes on similar parent materials.)
Land system	Catenary-based composite mapping unit that delineates topographically recurrent sequences of renewable natural resources, including soils, vegetation and hydrology
Climosequence	Large scale toposequence in which the differentiation of soils is due to significant differences in. altitude and climate between the upper and lower members. Usually not perceived as a catena

between parent materials are the dominant influences on soil formation and distribution. Similarly, catenary patterns were not strongly apparent in the soils of the island of Mafia (Fig. 2), where the variability of parent materials is the predominant pedogenic factor (AHT, 1980).

6. Diffusion of the catena

The formalised catena concept clearly fulfilled a widely-felt need, and was swiftly adopted by soil scientists beyond East Africa to structure their analyses, characterisation and mapping of soil-topography associations. It was soon widely used in soil studies throughout sub-Saharan Africa (Greene, 1947; Morison et al., 1948; Nye, 1954). Beyond Africa, Milne collaborated in its application to the soils of Indiana (Bushnell, 1943) and catenas have been, and still are, widely used to characterise soil distributions in the United States (Jauss et al., 2015; Nettleton et al., 1968; Sommer et al., 2000).

This diffusion means that that the term has been applied to a range of soil landscapes, and this has inevitably led to some broadening in its definition (Table 1). The catena is sometimes used just as a descriptor to indicate spatial patterns of soil/vegetation combinations that are consistently located in specific topographic positions. Used thus, it is more or less synonymous with 'toposequence'. The designation of a toposequence as a catena usually implies that the soils are not only spatially associated, but also pedologically linked (Young, 1976).

A crucial factor in the linkage is the movement of water (Greene, 1947). Incoming precipitation is partitioned between rapid evaporation, surface runoff, lateral subsurface throughflow, and vertical percolation to recharge groundwater. The seasonally poor drainage and high water-tables in the valley soils results from lateral run-on from upslope, and the intermediate soils on the lower slopes are imperfectly drained. This creates different weathering and leaching conditions in different parts of the slope, and can generate consistent topographically-related soil patterns. These are equivalent to the transformational catenas of Sommer and Schlichting (1997).

The redistributed water is rarely pure, and usually carries a load of dissolved and suspended materials that are translocated downslope (Greene, 1947; Khomo et al., 2013). The cations in the run-on water raise the pH and base saturation in the valley soils, which favours the development and stability of 2:1 smectitic clay minerals. In contrast, the loss of cations from the upslope soils tends to reduce pH and base saturation, which promotes desilication and the development of 1:1 kanditic aluminosilicates and reddish free sesquioxides. This accounts for the widespread 'dystric red slope over eutric black valley' soil patterns.

The movement of solids downslope as detached particles in surface wash, gradual whole-solum creep, or in intermittent whole-regolith mass movements contributes to the development of soil textural patterns in many translocational catenas (Milne, 1935b; Young, 1976). The complex textures of the Ukiriguru catena (Calton, 1963) may be partly due to vigorous surface wash, with coarser entrained particles from upslope deposited on the lower slope and finer clay particles on the valley floor.

Some catenary patterns do not depend directly on downslope water movement. Stream systems can dissect old stable land surfaces and strip off deep and intensely weathered regolith and soils when incising new valleys. The valley soils therefore develop in younger and less leached regoliths than those on the undissected upper slopes and crests (Spurr, 1955). Also, the older soils may have experienced paleoclimates that were moister than the present (Anderson, 2001; Milne, 1941).

All of the above factors and scenarios for catena development were recognised by the early soil scientists in East Africa. However, they appear to have identified catenas only on more or less lithologically homogeneous parent materials. Geological or compound catenas (Young, 1976) can develop where distinctly different parent materials are systematically associated with different slope positions (Table 1). The patterns are often due to differences in erodibility, with harder rocks persisting as interfluves and more erodible rocks flooring valleys. Compound catenas can be very complex. Thus, Neufeldt et al. (1999) characterised a catena in cerrado savannah in Brazil, with argillitic sedimentary rocks on the upper slope, sandy sedimentaries on the midslopes, basalts on the lower slopes, and mica schist in the valleys.

Most catenas derive from interactions of several processes and factors. Mass movements can modify the distribution of soil parent materials and make compound sequences appear less obviously catenary. In Tigray, Ethiopia, there are compound catenas where basalt outcrops upslope of limestone. This pattern generates lithologically heterogeneous compound catenas, but some of these are masked by large and laterally discontinuous mass movement lobes. Basaltic materials have slumped almost to the valley floor in places, effectively homogenising the regolith of the whole slope (Van de Wauw et al., 2008).

7. Catenas in non-savannah landscapes

Catenas develop best in savannah climates because the precipitation provides sufficient water to drive the translocation processes but does not flush the cations and sediments completely out of the landscape. However, catenas have also been identified in climates that are cooler, more arid or more humid than those of the savannahs.

The low rainfall in deserts leads to low leaching intensities, and cations are less readily moved laterally downslope (Yair, 1990). However, there appears to be some translocation, and the depths, size and forms of secondary carbonates may vary consistently with topographic position. Although total precipitations are low, the intensities of the rare rainfall events can be very high. Combined with low organic matter contents and weak topsoil structures, this can lead to episodic but substantial surface wash and mass movements, which can result in consistent topographically associated textural catenas.

In humid tropical forest climates cations are readily translocated but the plentiful rainfall often leaches them right out of the local landscape and into the stream network. Intra-catenary variations in pH and base status are therefore usually less apparent than in savannahs. However transformational, hydrological, and compound catenas (Table 1) may develop. Steeply dipping alternating sedimentary strata in Central Sarawak give rise to swarms of parallel, linear, and steeply homoclinal ridges on hard sandstones, with more erodible shales flooring the valleys. The ridge soils are moderately deep and well drained coarse loams. The shale soils on the lower slopes and in the valleys are shallower, less freely drained, and finer textured. All of the soils have low pH and exchangeable base contents (Scott, 1985). Catenas in temperate forest climates are often transformational hydrosequences, with markedly poorer soil drainage downslope, but without significant intra-catenary differentiation on base status (Glentworth and Dion, 1950).

8. Conclusions

The catena has greatly simplified soil mapping at medium and reconnaissance scales, at which individual soil series are too intricately distributed to be cartographically separable. Catenary distributions can be used to define composite soil mapping units that consist of series arrayed in systematic and consistent topographic patterns. Such units have been designated as toposequences (Jien et al., 2016), hydro-sequences (Smeck et al., 2002), associations (Glentworth and Dion, 1950) and recurrent landscape patterns (Webster and Beckett, 1970). The most widely used are land systems, which are topographically-associated mapping units that include other renewable natural resources as well as soils. Land systems were first formulated and applied to large underdeveloped areas of Australia (Christian et al., 1953). They were further developed in South Africa (Brink et al., 1965), following on from early applications of the catena in southern Africa (Watson, 1964; Webster, 1965). They have since been used for the pre-development resource mapping over large areas in Africa and elsewhere in the tropics, including several large surveys in East Africa (Ollier et al., 1969; King et al., 1982).

Although the catena was originally developed to clarify soil distributions at field scale, it has been most useful for small-scale mapping of large areas. Many examples of these early studies, including those of Milne and others consulted on for this paper are held in the WOSSAC international soils archive (Hallett et al., 2017). More recently the Catena concept has also proved useful as a sampling frame for more detailed isotope studies in tropical forests (Guédron et al., 2018).

The catena's integration of topographic patterns and linkages has led to its adoption beyond soil science. Catenas have been used for dating moraines and other glacial features (Bäumler, 2004; Berry, 1987). Geo-archaeological comparisons of fresh deposits with underlying paleosols down a catena can indicate climatic and/or land use changes (Beach et al., 2018). The emphasis on topographic linkage makes the catena an especially useful concept in hydrological connectivity studies (Francke et al., 2007). It has also been invoked in discussions of the spatial distribution, and floristic and structural diversity at intermediate scales in tropical forests (Duivenvoorden, 1995; Gentry, 1988).

The catena owes some of its continued relevance and durability to the way it enables scientists working in unfamiliar landscapes to disentangle what initially appear to be dauntingly complex patterns. The catena is also an insightful teaching aid, as the instructor can use it to explain the first steps in the analysis of soil landscapes. The simplicity, appeal and longevity of the concept is shown by the foundation, naming, and continuing impact of the international journal, 'Catena', which focuses on interdisciplinary aspects of soil science, hydrology, geomorphology, geoecology and landscape evolution.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2019.104291.

References

AHT, 1980. Land suitability survey. Phase I. Annexes 2 & 3. National Coconut Development Programme, Tanzania. Agrar-und-Hydrotechnik GmbH, Essen. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=22303).
Anderson, B., 1957. A survey of soils in the Kongwa and Nachingwea Districts of Tanganyika. University of Reading, Reading, pp. 120.
Anderson, B., p.c., 2001. Letter to Professor A. Young.
Anderson, G.D., 1962. A reconnaissance soil map of the Muheza area. Northern Research Centre (NRC), Ministry of Agriculture, Forests and Wildlife, Tengeru. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=311).
Baker, R.M., 1970. The Soils of Tanzania. FAO, Rome. (WOSSAC ID 44789. Access copyright restricted).
Barrera-Bassols, N., Zinck, J.A., 2003. Ethnopedology: a worldwide view on the soil knowledge of local people. Geoderma 111, 171–195. https://doi.org/10.1016/S0016-7061(02)00263-X.
Bäumler, R., 2004. Pedogenic studies in eastern Nepal—new aspects about the last glaciation. Quat. Sci. Rev. 23, 1777–1783. https://doi.org/10.1016/- j.quascirev.2004.03.003.
Beach, T., Ulmer, A., Cook, D., Brennan, M.L., Luzzadder-Beach, S., Doyle, C., Eshleman, S., Krause, S., Cortes-Rincon, M., Terry, R., 2018. Geoarchaeology and tropical forest soil catenas of northwestern Belize. Quat. Int. 463 A, 198–217. https://doi.org/10.1016/j.quaint.2017.02.031.
Berry, M.E., 1987. Morphological and chemical characteristics of soil catenas on Pinedale and Bull Lake Moraine slopes in the Salmon River Mountains, Idaho. Quat. Res. 28, 210–225. https://doi.org/10.1016/0033-5894(87)90060-3.
Brink, A.B.A., Mabbutt, J.A., Webster, R., Beckett, P.H.T. 1965. Report of the Working Group on land classification and data storage. Report. 940. Military Engineering Experimental Establishment. Christchurch.
Bonsteel, J.A., Fippin, E.O., Carter Jr., W.T., 1906. Soil Survey of Tompkins County, New York. Bureau of Soils, United States Department of Agriculture, Washington, D.C.
Brown, D.J., Clayton, M.K., McSweeney, K., 2004. Potential terrain controls on soil color, texture contrast and grain-size deposition for the original catena landscape in Uganda. Geoderma 122, 51–72. https://doi.org/10.1016/j.geoderma.2003.12.004.
Burtt, B.D., Welch, J.R., 1957. A field key to the savanna genera and species of trees, shrubs and climbing plants of Tanganyika Territory: Genera and some species. Government Printer, Dar es Salaam.
Bushnell, T.M., 1943. Some aspects of the soil catena concept. Soil Sci. Soc. Am. Proc. 7, 466.
Calton, W.E., Tidbury, G.E., Walker, G.F., 1955. A study of the more important soils of Zanzibar Protectorate. East African Agric. J. 21, 53–60. https://doi.org/10.1080/03670074.1955.11665005.
Calton, W.E., 1963. Some data on a Tanganyika catena. East African Agric. Forest. J. 29, 173–177.
Christian, C.S., Stewart, G.A., Nokes, L.C., Blake, S.T., 1953. General report on survey of Katherine-Darwin region. CSIRO, Melbourne.
Duivenvoorden, J.E., 1995. Tree species composition and rain forest-environment relationships in the middle Caquetá area, Colombia, NW Amazonia. Vegetatio 120, 9–113.
Francke, T., Güntner, A., Mamede, G., Müller, E.N., Bronstert, A., 2007. Automated catena-based discretization of landscapes for the derivation of hydrological modelling units. Int. J. Geogr. Inform. Sci. 22, 111–132. https://doi.org/10.1080/13658810701300873.
Gentry, A.H., 1988. Changes in plant community diversity and floristic composition on environmental and geographical gradients. Ann. Mo. Bot. Gard. 75, 1–34. http://www.jstor.org/stable/2399464.
Gethin-Jones, G.H., 1934. Tentative description of some 30 soil series of Kenya. Communication to 2nd conference of East African Soil Chemists, Zanzibar. Referenced in Milne 1935a, p. 196.
Gillman, C., 1949. A vegetation-types map of Tanganyika Territory. Geogr. Rev. 39, 7–37.

Glentworth, R., Dion, H.G., 1950. The association or hydrologic sequence in certain soils of the podzolic zone of North-East Scotland. J. Soil Sci. 1, 35–49.
Greene, H., 1947. Soil formation and water movement in the tropics. Soils Fertilisers 10, 253–256.
Grunwald, S. (Ed.) 2005. Environmental soil-landscape modelling. Geographic information technology and pedometrics. Taylor Francis, Boca Raton, Florida.
Guédron, S., Amouroux, D., Tessier, E., Grimaldi, C., Barre, J., Berail, S., Perrot, Grimaldi, M., 2018. Mercury isotopic fractionation during pedogenesis in a tropical forest soil catena (French Guiana): deciphering the impact of historical gold mining. Environ. Sci. Technol. 52 (20), 11573–11582. https://doi.org/10.1021/acs.est.8b02186.
Hall, A.D., Russell, E.J., 1911. Report on the Agriculture and Soils of Kent, Surrey and Sussex. Board of Agriculture and Fisheries, London.
Hallett, S.H., Sakrabani, R., Keay, C.A., Hannam, J.A., (2017) Developments in Land Information Systems: Case studies in land resource management capabilities and options. Soil Use Manage. 33, 514–529, doi: 10.1111/sum.12380.
Hoyle, B.S., 1987. Gillman of Tanganyika, 1882–1946: The life and work of a pioneer geographer. Gower, Aldershot, pp. 448.
Jauss, V., Johnson, M., Krull, E., Daub, M., Lehmann, J., 2015. Pyrogenic carbon controls across a soil catena in the Pacific Northwest. Catena 124, 53–59. https://doi.org/10.1016/j.catena.2014.09.001.
Jien, S.-H., Baillie, I., Hu, C.-C., Chen, T.-H., Isihikuza, Y., Chiu, C.-Y., 2016. Forms and distribution of phosphorus in a placic podzolic toposequence in subtropical subalpine forest, Taiwan. Catena 140, 145–154. https://doi.org/10.1016/j.catena.2016.01.024.
Khomo, L., Bern, C.R., Hartshorn, A.S., Rogers, K.H., Chadwick, O.A., 2013. Chemical transfers along slowly eroding catenas developed on granitic cratons in southern Africa. Geoderma 202–203, 192–202.
King, R.B., Rombulow-Pearce, C.W., Kikula, I.S., Ley G., 1982. Land system map of Mbeya Region. Report 26. Bureau of Land Use Planning, Dar es Salaam.
Krasilnikov, P.V., Tabor, J.A., 2003. Perspectives in utilitarian ethnopedology. Geoderma 111, 197–215. https://doi.org/10.1016/S0016-7061(02)00264-1.
Le Mare, P.H., 1972. A long term experiment on soil fertility and cotton yield in Tanzania. Exp. Agric. 8, 299–310.
Martin W.S., 1932. Letter to Geoffrey Milne. MSS Brit Emp.s.457 File 14, 32-33. Bodleian Library of Commonwealth and African Studies, Rhodes House, Oxford.
Milne, G., 1935a. Some suggested units of classification and mapping particularly for East African soils. Soil Research - Bodenkundliche Forschung, Supplement to the Proceedings of the International Union of Soil Science IV, 183-198.
Milne, G., 1935b. Composite units for the mapping of complex soil associations. Third Int. Cong. Soil Sci. 1, 345–347.
Milne, G., 1936a. Normal erosion as a factor in soil profile development. Nature 138, 548–549.
Milne, G, 1936b. A Soil Reconnaissance Journey in Parts of Tanga, East, Central & Lakes & Western Provinces of Tanganyika Territory. December 1935 to February 1936. Report prepared for the Acting Director of Agriculture, Department of Agriculture, Dar es Salaam. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=44718).
Milne, G., Beckley, V.A., Gethin Jones, G.H., Martin, W.S., Griffith, G., Raymond L.W., 1936. Provisional soil map of East Africa (Kenya, Uganda, Tanganyika, and Zanzibar) with explanatory memoir. Amani Memoirs. East African Agricultural Research Station, Amani. 34 pp. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=42187).
Milne, G., 1941. Report on a visit by the Soil Chemist to Certain Sisal Estates on the Central Railway, Tanganyika, 19 May to 3 June 1941. East African Agricultural Research Station, Amani. 13 pp. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=44725).
Milne, G., 1944. Soils in relation to population in West Usumbara. Geography 29, 107–113 (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=44893).
Milne, G., 1947. A soil reconnaissance journey through part of Tanganyika Territory December 1935 to February 1936. Journal of Ecology 35, 192- 265. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=131).
Ministry of Agriculture and Fisheries, 1928. Imperial Agricultural Research Conference, 1927. London.
Morison, C.G.T., Hoyle, A.C., Hope-Simpson, J.F., 1948. Tropical soil–vegetation catenas and mosaics: a study in the south western part of the Anglo-Egyptian Sudan. J. Ecol. 36, 1–84.
Morison, C.G.T., Wright, B.I., 1952. The Soils of Sukumaland. Department of Agriculture, Dar es Salaam.
Mugogo, S.E., Niemeyer, J.K.W., Mnari, Z.A., Kimaro, R., 1987. Soil and land suitability for irrigated agriculture of the Kitivo Village Irrigation Scheme, Tanga Region. Report D7, National Soil Service. Taro Agricultural Research Institute, Tanga. 52 pp.
Muir, A., Anderson, B., Stephen, I., 1957. Characteristics of some Tanganyikan soils. J. Soil Sci. 8, 1–20.
Nature, 1942., Obituary. Mr Geoffrey Milne. Nature, 149, 118. doi: 10.1038/149188b0.
Nettleton, W.D., Flach, K.W., Borst, G., 1968. A toposequence of soils in tonalite grus in the Southern California Peninsular Range. Soil Survey Investigations Report 21. Soil Conservation Service, Washington, D.C.
Neufeldt, H., Schneider, M. do O., Zech, W., 1999. Oxisol development along a compound catena of the Araguari River, Central Brazil. In: Thomas R., Ayarza M.A. (Eds.) Sustainable management for the Oxisols of the Latin American savannas. Centro Internacional de Agricultura Tropical, Cali. pp 10-21. < https://eref.uni-bayreuth.de/id/eprint/29995 > .
Nowell, W.M.,1930. First Annual Report, 1928-29. East African Agricultural Research Station, Amani. Government Printer, Dar es Salaam and H.M. Stationery Office, London.
Nye, P.H., 1954. Some soil-forming processes in the humid tropics: 1 A field study of a catena in the West African forest. J. Soil Sci. 5, 7–21.
Ollier, C. D., Webster, R., Lawrance, C.J., Beckett, P.H.T., 1969. Terrain classification and data storage. Land Systems of Uganda. MEXE Report 959, Christchurch, U.K. 234 pp.
Peat, J.E., Prentice, A.N., 1949. The maintenance of soil productivity in Sukumaland and adjacent areas, Tanganyika. East African. Agric. J. 15, 48–56. https://doi.org/10.1080/03670074.1949.11664708.
Phillips, J.F.V., 1929. Some important vegetation communities in the Central Province of Tanganyika Territory (formerly German East Africa). S. Afr. J. Sci. 26, 332–372.
Radwanski, S.A., Ollier, C.D., 1959. A study of an East African catena. J. Soil Sci. 10, 149–168 (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=25140).
Rehm, R.P.M., Grashey-Jansen, S., 2016. Soil sequence-studies on the tropical Buganda-Catena (Masaka District, Uganda). African J. Soil Sci. 4, 295–310.
Scott, I.M., 1985. The soils of Central Sarawak lowlands. East Malaysia. Soils Division, Department of Agriculture, Kuching. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=41359).
Smeck, N.M., Bigham, J.M., Guertal, W.F., Hall, G.F., 2002. Spatial distribution of lepidocrocite in a soil hydrosequence. Clay Miner. 37, 687–697.
Sommer, M., Schlichting, E., 1997. Archetypes of catenas in respect to matter - a concept for structuring and grouping catenas. Geoderma 76, 1–63.
Sommer, M., Halm, D., Weller, U., Zarei, M., Stahr, K., 2000. Lateral podzolization in a granite landscape. Soil Sci. Soc. Am. J. 64, 1434–1442.
Spurr, A.M.M., 1955. The soils of Mbozi (Mbeya District). Geological Survey Department, Dar es Salaam. (Accessed at http://www.wossac.com/search/wossac_ detail.cfm?ID=1535).
Szilas, C., Møberg, J.P., Borggaard, O.K., Johnson, M.R.S., 2005. Mineralogy of characteristic well-drained soils of sub-humid to humid Tanzania. Acta Agric. Scandinavica, Sect. B – Soil Plant Sci. 55 (4), 241–251. https://doi.org/10.1080/09064710500193360.
Watson, J.P., 1964. A soil catena on granite in Southern Rhodesia, I Field observations. J. Soil Sci. 15, 238–250. https://doi.org/10.1111/j.1365-2389.1964.tb02222.x.
Van de Wauw, J., Baert, G., Moeyersons, J., Nyssen, J., de Geyndt, K., Taha, N., Zenebe, A., Poesen, J., Deckers, J., 2008. Soil landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. Catena 75, 117–127. https://doi.org/10.1016/j.catena. 2008.04.006.
Webster, R., 1965. A catena of soils on the Norther Rhodesian plateau. J. Soil Sci. 16, 31–43. https://doi.org/10.1111/j.1365-2389.1965.tb01418.x.
Webster, R., Beckett, P.H.T., 1970. Terrain classification and evaluation using air photography: A review of recent work at Oxford. Photogrammetria 26, 51–75. https://doi.org/10.1016/0031-8663(70)90037-2.
Wengell A.R., Borden, R.W., Reinsborough J., 1969. Land Resources of Northwest Tanzania. Ministry of Agriculture of Agriculture and Cooperatives, Tanzania. (Accessed at http://www.wossac.com/search/wossac_detail.cfm?ID=41609).
Yair, A., 1990. The role of topography and surface cover upon soil formation along hillslopes in arid climates. Geomorphology 3, 287–299. https://doi.org/10.1016/0169-555X(90)90008-E.
Young, A., 1976. Tropical Soils and Soil Survey. Cambridge University Press, Cambridge.