# The distribution of trace and major elements in Kenyan soil profiles and implications for wildlife nutrition

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**Abstract:** Concentrations of trace and major elements are examined in several soil profiles from national parks and wildlife reserves in Kenya. Broad variations in soil trace element concentrations between locations are largely attributable to differences in parent material and variations in soil pH are related to sodium and calcium concentrations. However, element concentrations and distributions are also influenced by soil forming processes. The process of sodication in alkaline solonetz soils in Lake Nakuru National Park appears to have lowered the concentrations of copper, cobalt and nickel in the surface horizon. At Amboseli National Park, a marked accumulation of molybdenum, sodium, potassium, calcium and magnesium in the surface horizon of an alkaline solonchak is probably due to salinization processes. Apparent mobilization of copper, cobalt and nickel down the profile of a humic nitisol in the Aberdares Salient is associated with eluviation and leaching processes. In two andosols and an ando-humic nitisol, copper, cobalt and nickel tend to accumulate in the surface horizon in association with organic matter. In vertisols from Amboseli National Park and Lewa Downs Wildlife Reserve, the relatively constant trace element concentrations in the A and B horizons are linked to the self-swallowing processes that characterize this soil type. The elevated pH in the solonetz and solonchak soils at Lake Nakuru and Amboseli National Parks results in enhanced uptake of molybdenum in the grass species *Sporobulus spicatus*. At Lake Nakuru National Park, high molybdenum concentrations in this and other plant species are associated with low copper status of impala. The implications of soil geochemistry for the trace element nutrition of wild animals in small conservation areas are discussed.

The trace element status of animals depends strongly on that of their diet (Underwood 1977). For wildlife, studies have demonstrated that the distribution and seasonal movements of some species are related to concentrations of major and trace elements in grasses (McNaughton 1988, 1990; Ben-Shahar & Coe 1992). The enclosure of wildlife within relatively small national parks has focused attention on the capacity of soils to release adequate trace elements into the food chain. The uptake of a trace element into a plant depends on the plant species and on a number of soil properties which determine the bioavailability of the element in the soil. These soil properties include the total concentration of the element, soil pH, moisture content, organic matter content, clay content and redox conditions and are ultimately determined by both the parent material and the soil forming processes.

Previous geochemical studies in national parks and wildlife reserves in Kenya have shown that broad variations of the trace element content of soils were largely attributable to differences in soil parent material (Maskall & Thornton 1991). In a study of Mole National Park in Ghana, Bowell & Ansah (1993) found that bedrock geology was the major control on concentrations of cobalt, copper, manganese and selenium in soils. However, within particular locations, local pedogenic and hydrological factors appeared to influence the total concentration of trace elements in surface soils and their bioavailability to plants (Maskall & Thornton 1991). To investigate the influence of these factors in greater detail, the geochemistry and pedology of a number of soil profiles from wildlife conservation areas in Kenya was examined, and the implications for the trace element nutrition of wild animals evaluated.

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## Methodology

Soil profiles were examined at naturally occurring or man-made soil exposures or by digging a pit to a maximum depth of 2 m. Individual horizons were characterized for colour using Munsell soil colour charts and for texture and

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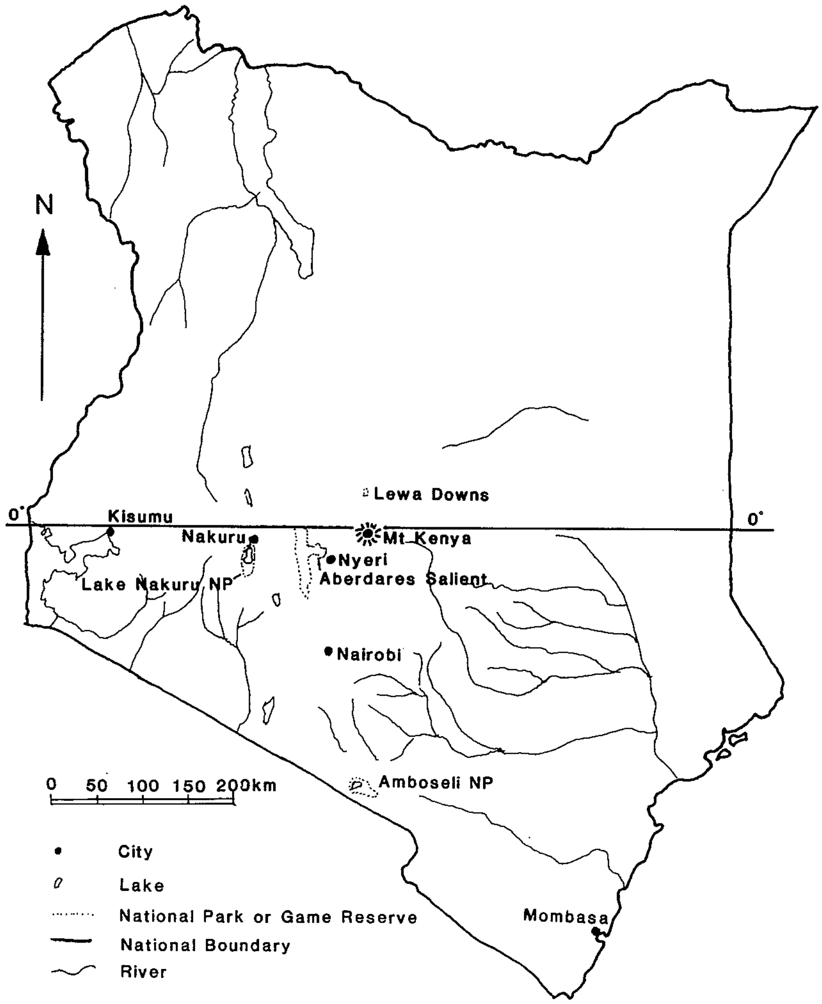


**Fig. 1.** Sampling locations in Kenya.

wetness by hand (Faniran & Areola 1978). One soil sample was taken from each horizon or sub-horizon which varied in thickness according to the profile characteristics. Each sample comprised between 800 and 900 g of material which was removed from a freshly exposed face of the profile using a trowel. All soil samples were sun-dried, disaggregated, homogenized and passed through a 2 mm sieve in Kenya. For the soil samples, *c.* 400 g of material was transported to Imperial College, London. On arrival, samples were redried, rehomogenized and *c.* 35 g of material ground to less than 180 mm. 'Total' concentrations of trace and major elements were determined by digesting a 0.25 g sample of the $<180\,\mu m$ soil fraction with a concentrated nitric/perchloric acid mixture and analysing by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) (Thompson & Walsh 1983). The total soil molybdenum concentration was determined by ICP-AES after extraction into heptan-2-one giving a detection limit of $0.06\,\mu g\,g^{-1}$ (Thompson & Zao 1985). Soils were analysed for pH by the method of Allen *et al.* (1974). Organic matter in non-sodic, non-calcic soils was determined using a soil ignition method. The loss in weight of a 5 g soil sample was measured after ignition at a temperature of 450°C (Allen *et al.* 1974). At Amboseli National Park, surface soils (0–15 cm) and grass samples were also taken as part of the reconnaissance survey of the area. Surface soils were collected using a 2.5 cm diameter soil auger and each sample comprised a composite of nine subsam-

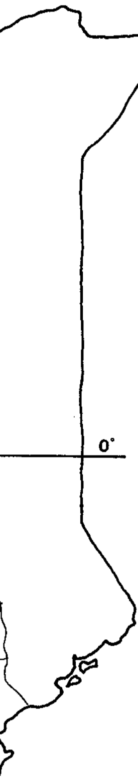


**Table 1.** *Climate and altitude of sampling sites*

| Location | | Mean temp. (°C) | Annual rainfall (mm) | Altitude (m) |
|---|---|---|---|---|
| Lake Nakuru N.P. | | 18 | 876 | 1800 |
| Aberdares Salient | East | 18 | 700 | 1900 |
| | West | 13 | 1300 | 2300 |
| Amboseli N.P. | | 23 | 350–400 | 1250 |
| Lewa Downs W.R. | | 18–20 | 450–900 | 1800 |

Sources: Sombroek *et al.* (1982); Vareschi (1982); Western (1969).

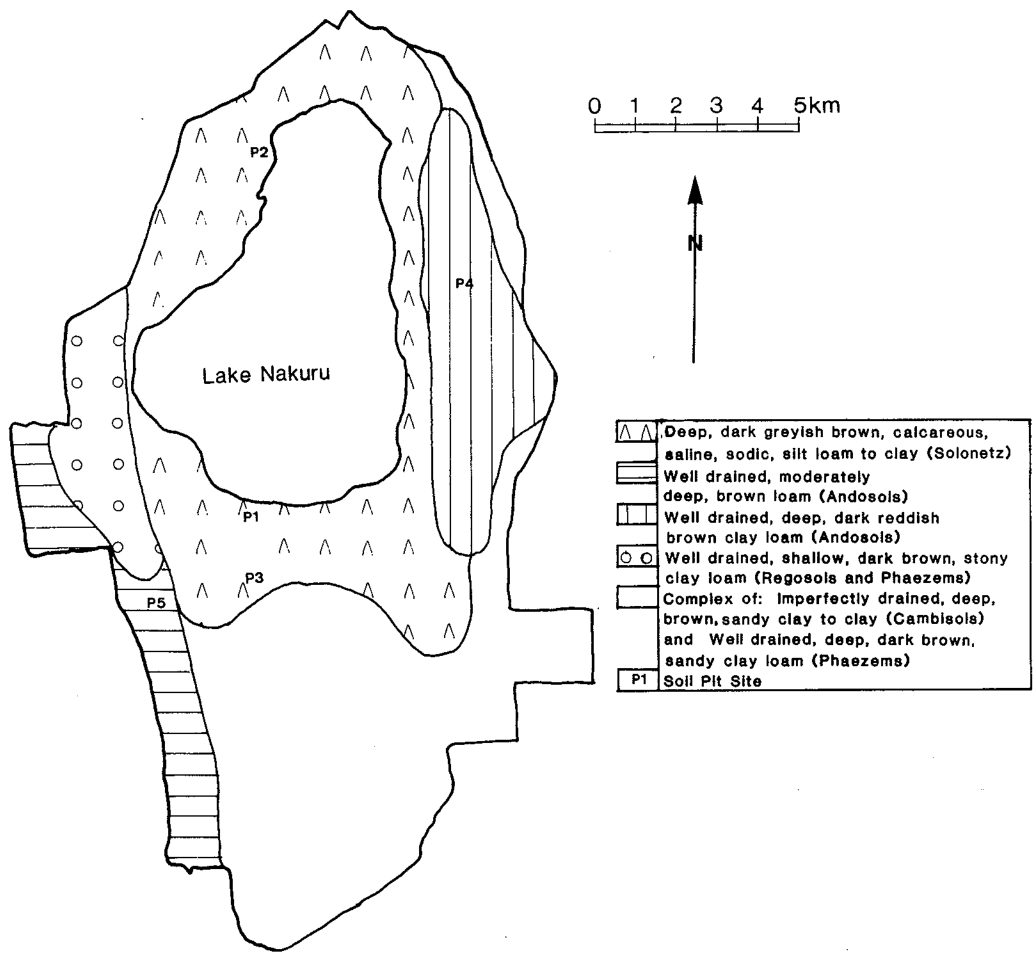


**Fig. 2.** Soils of Lake Nakuru National Park. Source: Sombroek *et al.* (1982).

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ples taken on a 4 × 4 m square. Soils were then treated as described above. Grass samples were collected using scissors within the 4 × 4 m square, sun-dried in Kenya and transported to Imperial College. Plant samples were redried, milled and analysed for trace element content by ICP-AES after digestion with nitric and perchloric acids (Thompson & Walsh 1983). Data were assessed for accuracy and precision using a quality control system integral to the analytical procedure (Ramsey *et al.* 1987). All data achieved the precision and accuracy targets of 10%.

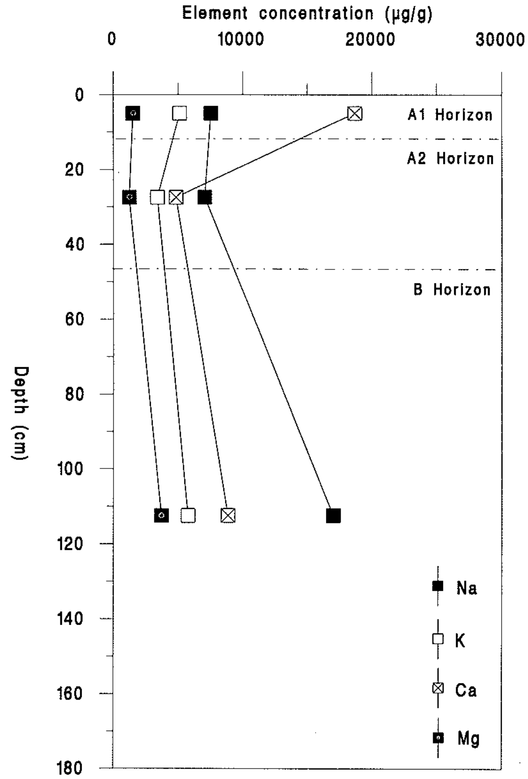


**Fig. 3.** Profile 1: variation of major element concentrations with depth.

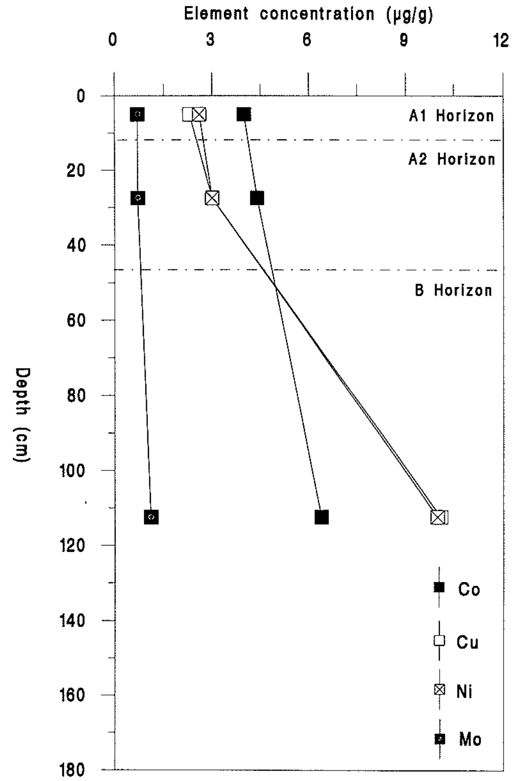


**Fig. 4.** Profile 1: variation of trace element concentrations with depth.

## Site descriptions and results

Four conservation areas were studied, their locations in Kenya are shown in Fig. 1 and climatic data are given in Table 1. Ten soil profiles were examined and the full datasets have been deposited with the Geological Society Library and the British Library Document Supply Centre, Boston Spa, Wetherby LS23 7BQ, UK, as Supplementary Publication No. SUP18110 (13 pp). The Supplementary Publication contains data on pH and the following elements in the ten profiles: sodium, potassium, calcium, magnesium, aluminium, manganese, iron, cobalt, copper, nickel, zinc and molybdenum. In addition, the organic matter content is given for Profiles 5, 6, 9 and 10. In this paper, data for eight elements and soil pH are presented for Profiles 1, 5, 6, 8 and 10 only.

### *Lake Nakuru National Park*

The park covers an area of 180 km$^2$ in the Rift Valley of which 40 km$^2$ are occupied by the lake. The floor of the Rift Valley around Nakuru belongs to a Tertiary–Quaternary volcanic suite with associated alkaline sediments (McCall 1967). Lake Nakuru is the low point in a catchment basin of *c.* 1800 km$^2$ bounded to the west by the fault scarp of the Mau. To the east of the lake lies Lion Hill, originally a subsidiary volcano of the lower Menengai succession. Lake Nakuru is a hypereutrophic, alkaline–saline closed basin system which deposits trona at times of low water (Vareschi 1982). Soils on the Rift Valley floor are derived from sediments of volcanic and lacustrine origin, giving rise to dark, poorly drained clays being more calcareous, saline and sodic near to the lake (Fig. 2). The Mau escarpment and Lion Hill are mantled by andosols developed over phonolites and phonolitic trachytes (Sombroek *et al.* 1982).

Five profiles were studied:

*Profile 1:* solonetz developed on lake sediments located 200 m south of Lake Nakuru on flats with a patchy covering of the grass *Sporobulus spicatus*.

*Profile 2:* solonetz developed on lake sediments located 500 m west of Lake Nakuru in dense *Acacia xanthophloea* forest.

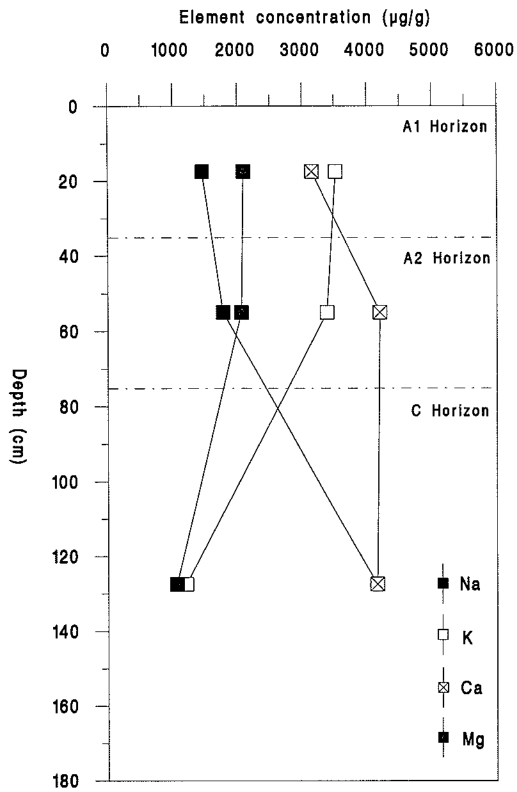


**Fig. 5.** Profile 5: variation of major element concentrations with depth.

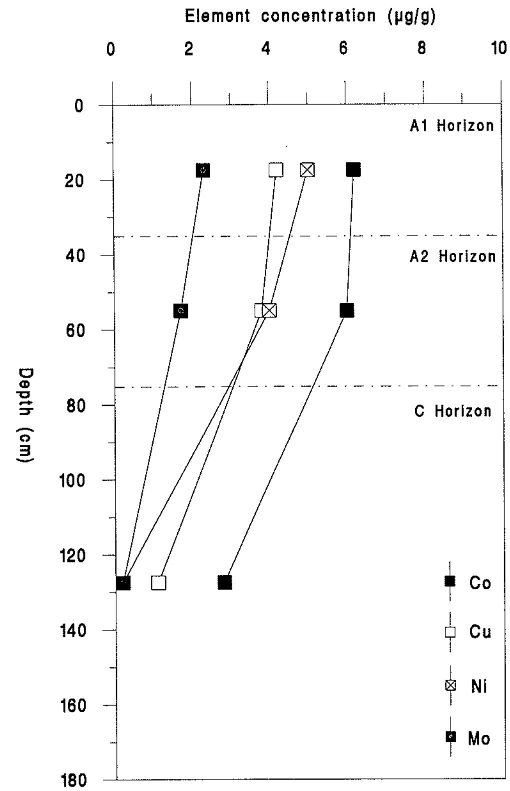


**Fig. 6.** Profile 5: variation of trace element concentrations with depth.

*Profile 3:* solonetz developed on lake sediments located 2000 m south of Lake Nakuru in open *Cynodon dactylon*/*Chloris gayana* grassland.
*Profile 4:* humic andosol developed on a phonolitic trachyte located on Lion Hill in *Tarchonanthus camphoratus* scrub.
*Profile 5:* vitric andosol developed on a phonolite located on the Mau Escarpment in mixed *Acacia xanthophloea*/*Tarchonanthus camphoratus* woodland.

The solonetz soils feature a relatively narrow A horizon with a sandy loam or sandy silt loam texture and a thicker B horizon with a clay-rich texture. The profiles have a high pH (6.6–11.1) and elevated concentrations of sodium (4190–19660 $\mu g\,g^{-1}$) and calcium (1705–51800 $\mu g\,g^{-1}$). Trace element concentrations in the surface horizon of the solonetz soils are low; mean concentrations of cobalt, copper, nickel and molybdenum are 3.9, 3.5, 2.9, and 0.9 $\mu g\,g^{-1}$ respectively. In general, elemental concentrations tend to reach a maximum in the B horizon and this is illustrated for Profile 1 in Figs 3 and 4. Soil pH also increases with depth reaching a maximum in the B horizon (Fig. 13).

The andosols both comprise a dark reddish–brown humic A horizon with a silty clay loam texture which directly overlies the C horizon. The geochemistry of both profiles is similar and the elemental data for Profile 5 are presented here. Sodium and calcium concentrations increase down the profile whereas potassium and magnesium decrease with depth (Fig. 5). The pH of the $A_1$ horizon is 6.7 which increases to 8.7 in the C horizon (Fig. 13). Trace element concentrations in the surface horizon are 6.2 $\mu g\,g^{-1}$ cobalt, 4.2 $\mu g\,g^{-1}$ copper, 5.0 $\mu g\,g^{-1}$ nickel and 2.3 $\mu g\,g^{-1}$ molybdenum. The trace elements are accumulated in the A horizon relative to the C horizon (Fig. 6) and may be associated with organic matter.

## *Amboseli National Park*

Amboseli is located in the south of Kenya a few kilometres from the Tanzanian border (Fig. 1). The area has a lower rainfall, lower altitude and higher temperatures compared with the other

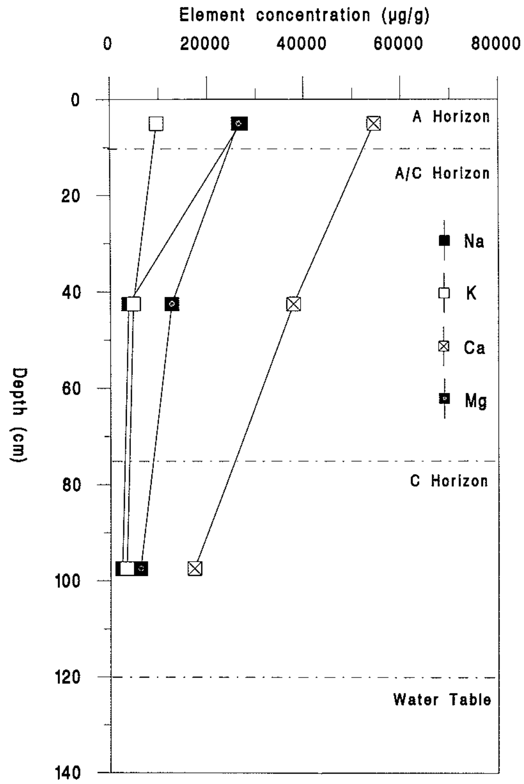


**Fig. 7.** Profile 6: variation of major element concentrations with depth.

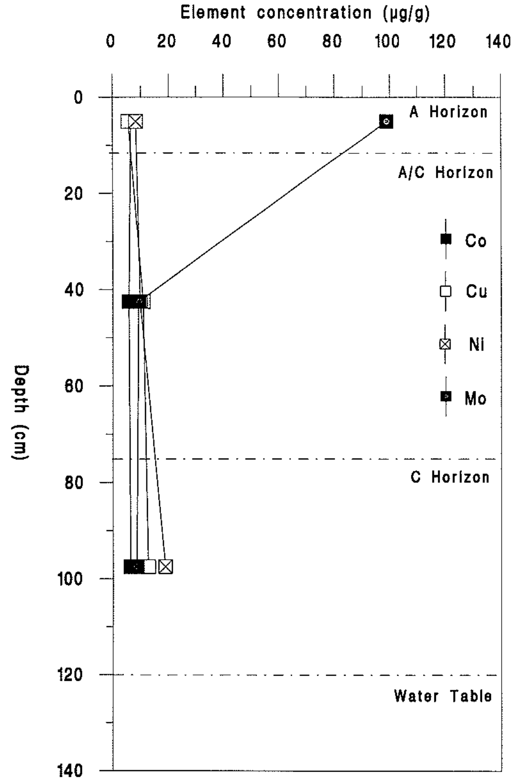


**Fig. 8.** Profile 6: variation of trace element concentrations with depth.

sites (Table 1). A small part of the park of about 30 km$^2$ in area was studied, located in the Ol Tukai/Longinye area. The emergence of the Kilimanjaro volcanics in the late Pliocene produced basaltic lavas which flowed into the south of the study area. Subsequent infilling of the Amboseli basin occurred by deposition of gravels, silts and sands from rivers to the north and west and deposition of ashes, clays and conglomerates from Kilimanjaro (Williams 1972).

Two soil profiles were studied.

*Profile 6:* orthic solonchak located on the Ol Tukai salt pan developed on a parent material of clays, calcareous silts and silty clays. The pan supports a patchy covering of the grass *Sporobulus spicatus*.

*Profile 7:* chromic vertisol located to the south of the Engong Narok swamp developed on infill from basaltic rocks. No vegetation cover.

The solonchak comprises a light grey crust underlain by a narrow, sandy, pale brown A horizon, an intermediate A/C horizon and a dark greyish-brown C horizon with a silty sand loam texture. The water table was present at a depth of 1.2 m. The profile has a high pH (9.2–10.7) and high concentrations of sodium (2372–26980 $\mu g\,g^{-1}$) and calcium (17240–54500 $\mu g\,g^{-1}$). Sodium, potassium, calcium and magnesium are accumulated in the A horizon (Fig. 7) which also has the highest pH (Fig. 13). The molybdenum concentration in the A horizon is nearly 100 $\mu g\,g^{-1}$, over ten times that in the C horizon (Fig. 8). In contrast, cobalt, copper and nickel concentrations are low and tend to increase with depth.

## *Aberdares Salient*

The Salient is a wedge-shaped area on the slopes of the Aberdare mountain range composed of the footridges of old basaltic volcanoes. It covers an area of about 70 km$^2$, the predominant vegetation being montane forest and associated scrub and clearings. The area receives a relatively high level of rainfall particularly on its

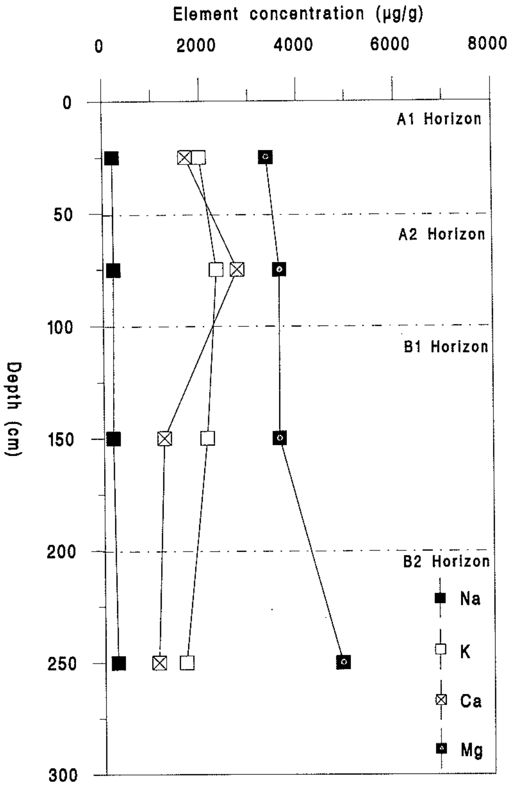


**Fig. 9.** Profile 8: variation of major element concentrations with depth.

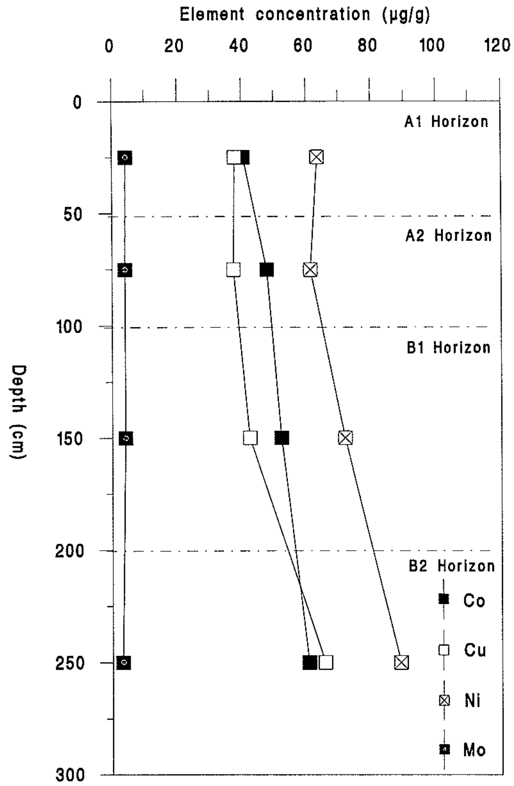


**Fig. 10.** Profile 8: variation of trace element concentrations with depth.

upper slopes to the west (Table 1). The Salient is entirely underlain by lavas of the Laikipian and Sattima series (Shackleton 1945). In the east of the Salient, soils are classed as humic nitisols and in the west as a complex of ando-humic nitisols and humic andosols (Sombroek *et al.* 1982). This classification reflects the increase in the proportion of volcanic ash in the soil parent material in the west.

Two profiles were studied.

*Profile 8:* humic nitisol developed on basalt from the extreme east of the area at an altitude of 1920 m. The exposure is located in a clearing in dry intermediate forest.

*Profile 9:* ando-humic nitisol developed on basalt/volcanic ash in the northwest of the salient at an altitude of 2280 m. Vegetation is dominated by dense montane forest.

The nitisols are both relatively deep, dark reddish-brown, silty clay loams and the humic nitisol has a thick argillic B horizon. Soil organic matter is generally in the range 10–12% but is markedly higher (21.5%) in the $A_1$ horizon of the ando-humic nitisol. Base cation concentrations are relatively low (Fig. 9), particularly for sodium (89–261 $\mu g\,g^{-1}$) and calcium (163–2761 $\mu g\,g^{-1}$) and the soils have a relatively low pH (4.2–6.4). The nitisols are relatively rich in trace elements; the $A_1$ horizon of the humic nitisol contains 40.6, 37.9, 63.4 and 4.2 $\mu g\,g^{-1}$ of cobalt, copper, nickel and molybdenum respectively. In the humic nitisol (Profile 8) cobalt, copper and nickel concentrations increase down the soil profile (Fig. 10) but in the ando-humic nitisol (Profile 9), trace element concentrations are higher in the A horizon.

## *Lewa Downs Wildlife Reserve*

Lewa Downs is a small wildlife reserve located on ranchland in the central highlands at an altitude of about 1800 m (Table 1). The 14 $km^2$ area is predominantly underlain by the Osirua basalts which vary from olivine–augite basalts to mugearites and basanites (Hackman 1988). Data are presented here for the predominant soil type:

*Profile 10:* chromic vertisol developed on basalt located in open grassland.

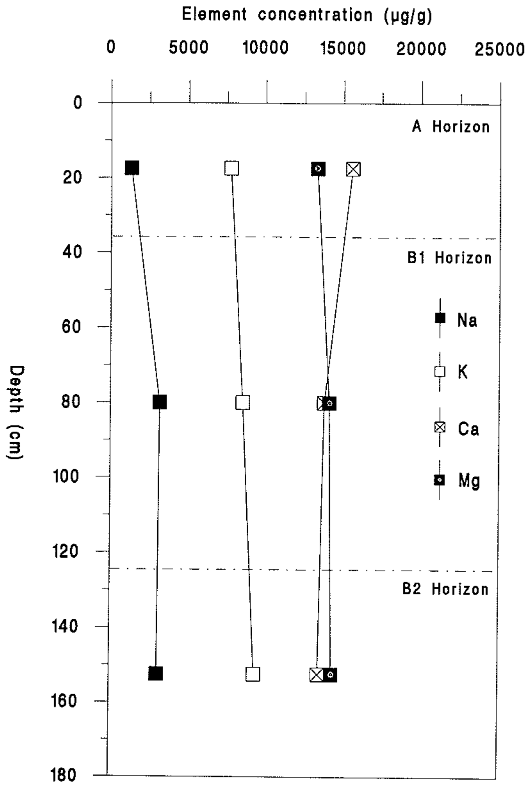


Fig. 11. Profile 10: variation of major element concentrations with depth.

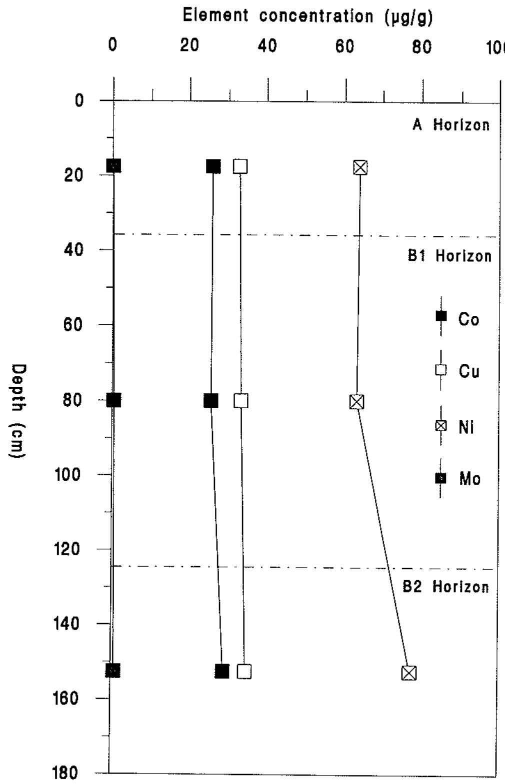


Fig. 12. Profile 10: variation of trace element concentrations with depth.

The soil profile features a dark grey A horizon with a clay texture and significant cracking and crumbly consistency. The $B_1$ and $B_2$ horizons are relatively deep and show relatively little differentiation although there is some cracking in the $B_1$. Soil pH remains at a constant 8.5 (Fig. 13). The soil contains high concentrations of calcium (13430–15560 $\mu g\,g^{-1}$) and magnesium (13280–14290 $\mu g\,g^{-1}$) throughout the profile (Fig. 11). Concentrations of copper, cobalt, zinc and nickel show little significant variation with depth (Fig. 12). However, molybdenum is depleted in the A horizon (0.1 $\mu g\,g^{-1}$) relative to the $B_1$ horizon (0.4 $\mu g\,g^{-1}$) and the $B_2$ horizon (0.7 $\mu g\,g^{-1}$).

## Discussion

### *The influence of parent material on element concentrations in soils*

Throughout Africa, relatively high concentrations of copper and cobalt have been reported in a variety of soils derived from basic rocks; from basalts and amphibolites in Nigeria (Cottenie *et al.* 1981); from amphibolites in the Central African Republic (Boulvert 1966); from dolerite and basalt in Chad (Pias 1968); and from basic rocks in Ghana (Burridge & Ahn 1965) and Angola (Fragoso 1959). Low concentrations of copper and cobalt have been reported in soils developed on volcanic ash and lake sediments in Kenya (Chamberlain 1959; Nyandat & Ochieng 1976; Maskall & Thornton 1991). The broad variations in soil trace element concentrations between the study locations are largely attributable to differences in parent material. Thus at Lake Nakuru National Park, the solonetz soils which are developed on old lake sediments and the andosols which are developed on phonolites and phonolitic trachytes contain relatively low concentrations of copper, cobalt and nickel. Conversely, soils developed on basalts at the Aberdares Salient, Amboseli and Lewa Downs have relatively high copper, cobalt and nickel concentrations. It is interesting to note that concentrations of iron correlate significantly with those of copper ($r = 0.59$), cobalt (0.85) and nickel (0.53) for all sites. In some profiles,

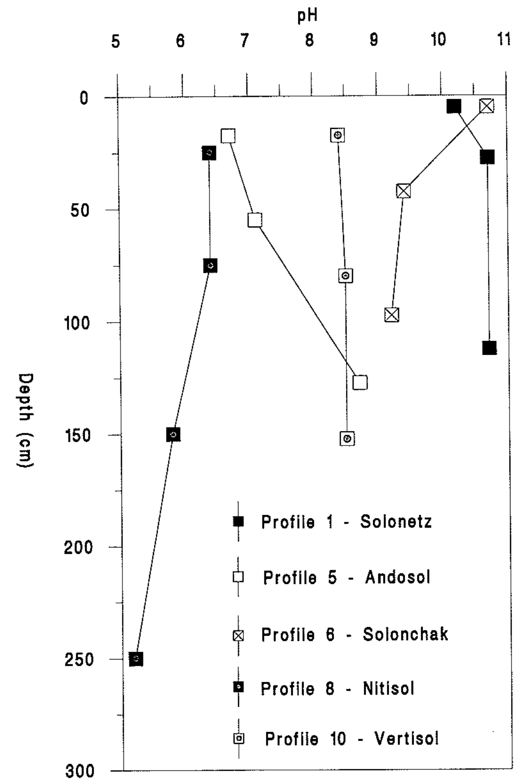


**Fig. 13.** Variation of soil pH with depth.

the concentrations of major elements in soil are influenced by the chemical composition of the parent material as indicated by the geochemistry of the C horizon. The high calcium concentrations in the solonchak at Amboseli appear to derive from the calcareous nature of the sedimentary parent material. Similarly, the high concentrations of calcium and magnesium in the vertisol at Lewa Downs probably originate from the underlying basaltic rocks. The relatively high sodium concentrations in the andosols at Lake Nakuru National Park reflect the composition of the underlying phonolitic trachytes and phonolites which are both relatively rich in sodium (McCall & Hornung 1972).

## *The influence of pedogenic processes on element distribution in soil profiles*

Previous work has indicated that variations in soil trace element concentrations were influenced by the action of pedogenic processes, particularly in ferrisols and ferralsols (Aubert & Pinta 1977). In the Central African Republic ferrisols derived from charnockite, gneiss or migmatite had either very low (traces–1 $\mu g\,g^{-1}$), average (10–30 $\mu g\,g^{-1}$) or very high (100–200 $\mu g\,g^{-1}$) total copper concentrations, depending on the degree of rock weathering and soil leaching (Boulvert 1966). For ferralsols derived from basalts in Polynesia, the cobalt concentration varied from 5–25 $\mu g\,g^{-1}$ depending on the state of soil degradation (Tercenier 1963). Nalovic (1969) reported that in Madagascar, the range of soil cobalt concentrations expected from soil parent materials appeared reversed and attributed this to soil degradation factors; ferralsolic soils developed on basalts had lower concentrations of cobalt (trace–3 $\mu g\,g^{-1}$) than those developed on granite or limestone (15–20 $\mu g\,g^{-1}$). In this study, there is evidence that pedogenic factors can affect the trace element distribution in a range of soil types.

Solonetz soils develop in the presence of sodium cations and carbonate and bicarbonate anions, high concentrations of which have been reported in Lake Nakuru (McCall 1967). In the lake water, sodium accounts for 96% of the total cations whilst carbonate and bicarbonate account for 84% of the total anions (Vareschi 1982). According to Buringh (1979) the presence of highly soluble salts such as $NaHCO_3$ and $Na_2CO_3$ results in some calcium ions being replaced by sodium ions on the soil exchange complex. This process, termed sodication, allows clay particles and humus to be easily eluviated from the A horizon to the B horizon given sufficient rainfall. Thus, trace elements bonded to clay particles and humus would also be eluviated, or possibly leached, from the A horizon to the B horizon. This process creates a typical solonetz profile with an A horizon of a mineral, coarse-grained nature and a natric B horizon, rich in clay with higher concentrations of trace elements. Profile 1, 200 m from Lake Nakuru, fits this description almost exactly, suggesting that sodication is active in this area. At Profiles 2 and 3, the textural and chemical gradients associated with the solonetz profile are also present but are not as marked as in Profile 1.

In semi-arid areas, rainfall can be insufficient to remove soluble salts from the soil (Bridges 1978). Instead, salts in solution are drawn upwards through the soil profile by capillary action and are deposited at the surface as the water is evaporated. This process of salinization produces solonchak soils such as that examined at Amboseli National Park. In this case, the upward movement of water containing high

**Table 2.** *Element concentrations ($\mu g\,g^{-1}$) in surface soils (0–15 cm): orthic solonchak, Amboseli National Park*

| | Arith. mean | Range | SD | n |
|---|---|---|---|---|
| Sodium | 13897 | 6010–26120 | 6535 | 6 |
| Potassium | 13038 | 7080–22740 | 5005 | 6 |
| Calcium | 53375 | 23870–85300 | 19230 | 6 |
| Magnesium | 27322 | 14910–38500 | 7744 | 6 |
| Molybdenum | 25.2 | 3.0–41.0 | 13.6 | 6 |

concentrations of sodium, potassium, calcium and magnesium has resulted in the accumulation of these elements in the A horizon. In addition, the same process appears to have led to the accumulation in the A horizon of molybdenum, a phenomenon which has not been previously reported. At the prevailing pH of 9.2–10.7 in this soil, the most stable form of molybdenum over a wide range of Eh is the highly soluble molybdate anion (Brookins 1988). The accumulation of sodium, potassium, calcium, magnesium and molybdenum in surface soils may be occurring throughout the Ol Tukai Salt Pan. In the reconnaissance survey of the area, where samples were taken on a 2 km grid, elevated concentrations of these elements were found in the top 0–15 cm of the solonchak soil (Table 2). Relatively high molybdenum concentrations of between 11 and 16 $\mu g\,g^{-1}$ have also been reported in the top 30 cm of a solonchak in Mole National Park, Ghana (Bowell & Ansah 1993).

Nitisols develop in a relatively intense weathering regime and in the Aberdares Salient this is reflected in the soils by the low concentrations of base cations. Similar geochemistry has been recorded for ferralsols (Bowell 1993) although in general these soils develop in hotter, more humid environments than nitisols. In the eastern Salient, the characteristic argillic B horizon in the humic nitisol results from the eluviation of clay down the profile (Sombroek *et al.* 1982). Trace elements associated with clay particles appear to have been eluviated from the A horizon to the B horizon although leaching may also be responsible. Variations in trace element concentration have been associated with clay content in other tropical soils (Nalovic 1969; Bleeker & Austin, 1970). In the andosols in Lake Nakuru National Park and the ando-humic nitisol in the western Aberdares Salient, some trace elements are accumulated in the A horizon. Combining the data for these three profiles, concentrations of cobalt, copper and nickel show a significant relationship to organic matter content ($p < 0.05$). Similar trace element enrichment by organic matter has also been reported in ferralsols in Ghana (Bowell 1993).

Vertisols develop on parent materials rich in calcium and magnesium in hot climates with pronounced seasonal contrasts (Duchaufour 1982). A characteristic homogeneous profile is produced by the 'self-swallowing' process resulting from the alternate shrinking and swelling of montmorillonite clays. In the dry season, surface soil falls down the deep cracks formed by clay shrinkage whilst in the wet season, clay swelling causes the cracks to close and squeezes material back up to the surface. The vertisols at both Amboseli and Lewa Downs have an A horizon with a loose, powdery consistency and have cracks extending to a depth of at least 50 cm. In addition, both profiles have the high calcium and magnesium concentrations associated with montmorillonite clays. Concentrations of cobalt, copper and nickel are relatively constant in the A and B horizons at both sites. This may be related to the homogenization of soils due to the self-swallowing processes active in the profiles.

## *Soil–plant uptake of trace elements*

The transfer of a trace element from soil to plant depends not only on the total amount of the element present but on soil factors which affect its bioavailability and plant factors which determine its rate of uptake. The soil parent material has been found to have some influence on trace element bioavailability such as in the Kenyan Rift Valley where soils derived from volcanic ash, pumice and lake sediments have been found to be low in acetic acid extractable cobalt (Chamberlain 1959) and in EDTA extractable copper (Nyandat & Ochieng 1976; Maskall & Thornton 1992). Soil pH has a strong influence on metal availability and in alkali soils the elevated pH generally results in increased bioavailability of molybdenum and selenium whilst the bio-availability of copper, cobalt and nickel decrease (Adriano 1986). Copper uptake in wheat was found to decrease with increasing pH in several Kenyan soils (Nyandat & Ochieng 1976). An increase in the trace element content of plants in the wet season has been observed for pastures in the Kenya highlands (Howard *et al.* 1962), for grass species adjacent to Lake Nakuru

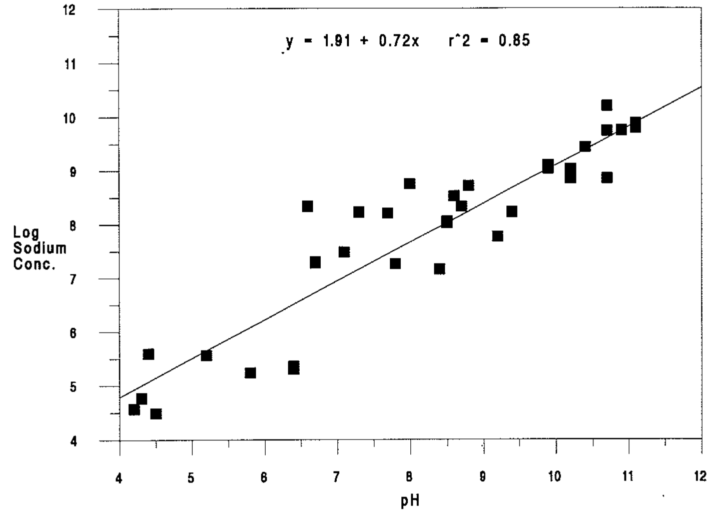


**Fig. 14.** Variation of soil pH with log sodium concentration.

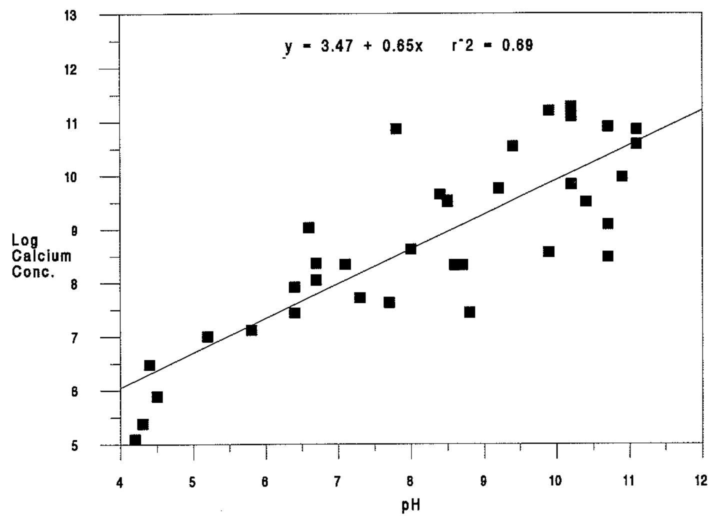


**Fig. 15.** Variation of soil pH with log calcium concentration.

in the Rift Valley (Maskall 1991) and for several grass and browse species in Mole National Park in Ghana (Bowell & Ansah 1993). Trace element concentrations in tropical pastures can fall as the plant matures (Gomide *et al.* 1969) and during periods of rapid growth (Fleming 1973). Significant differences in trace element content can occur between plant species in tropical areas, particularly between grasses and browse plants (Tartour 1966; Reid *et al.* 1979; Ben-Shahar & Coe 1992).

In the soils under study the bioavailability of trace elements appears to be strongly influenced by the soil pH which varies considerably and is related to the concentrations of sodium and calcium (Figs 14, 15). At Lake Nakuru National Park, the elevated pH of soils has been linked with the high molybdenum content of several plant species (Maskall & Thornton 1992). Particularly high concentrations of molybdenum up to a maximum of 69 $\mu g\,g^{-1}$ were found in the alkali tolerant grass species *Sporobulus spicatus* which grows on the solonetz soils adjacent to the lake (Table 3). Grasses sampled in the park tended to contain higher concentrations of copper and cobalt and lower concentrations of

**Table 3.** *Trace element concentrations (μg g⁻¹ D.M.) in plants, Lake Nakuru National Park*

| | | Mean[1] | n[1] | Mean[2] | n[2] |
|---|---|---|---|---|---|
| *Cynodon dactylon* | Cu | 11.1 | 89 | 3.5 | 33 |
| (Star Grass) | Co | 0.4 | 89 | 0.2 | 33 |
| | Mo | 2.2 | 89 | 3.4 | 33 |
| | Se | 0.2 | 80 | – | – |
| *Themeda triandra* | Cu | 18.5 | 6 | 7.6 | 8 |
| (Red Oat Grass) | Co | 0.5 | 6 | 0.2 | 8 |
| | Mo | 2.4 | 6 | 2.6 | 8 |
| | Se | 0.1 | 6 | – | – |
| *Sporobulus spicatus* | Cu | 11.7 | 4 | 5.4 | 18 |
| (Soda Grass) | Co | 0.7 | 4 | 0.2 | 18 |
| | Mo | 8.9 | 4 | 18.1 | 18 |
| | Se | 0.3 | 4 | – | – |
| *Acacia xanthophloea* | Cu | 2.6 | 50 | 1.9 | 9 |
| (Yellowthorn Tree) | Co | 0.1 | 50 | 0.2 | 9 |
| | Mo | 2.5 | 50 | 1.7 | 9 |
| | Se | 0.6 | 40 | – | – |
| *Solanum incanum* | Cu | 5.7 | 24 | 5.1 | 23 |
| (Sodom Apple Bush) | Co | 0.3 | 24 | 0.3 | 23 |
| | Mo | 3.2 | 24 | 2.3 | 23 |
| | Se | 0.4 | 24 | – | – |

[1] Reconnaissance survey, Maskall & Thornton (1991).
[2] Biogeochemical zones survey, Maskall & Thornton (1992).

**Table 4.** *Trace element concentrations (μg g⁻¹ D.M.) in Sporobulus spicatus, Amboseli National Park*

| | Arith Mean | Range | SD | n |
|---|---|---|---|---|
| Cobalt | 0.4 | 0.3–0.8 | 0.2 | 5 |
| Copper | 3.6 | 1.7–5.4 | 1.7 | 5 |
| Molybdenum | 86.2 | 19.4–152.0 | 50.9 | 5 |

selenium than did the browse plants (Table 3). High molybdenum levels averaging over 80 μg g⁻¹ were also found in *Sporobulus spicatus* on the alkaline solonchak soils at Amboseli National Park (Table 4). This was attributed to a combination of enhanced molybdenum uptake into the grass and the presence of windblown soil particles on the leaf surfaces of the plant.

## *Implications for wildlife nutrition*

McNaughton & Georgiadis (1986) proposed that many African herbivores were existing in a vague, qualitative state of undernutrition and that this had a strong influence on their foraging behaviour and dynamics. A subsequent study showed that the spatial distribution of animals in the Serengeti National Park in Tanzania was related to the mineral content of forages and that magnesium, sodium and phosphorus appeared particularly important (McNaughton 1988). A further study found that the seasonal movements of migratory grazers in the Serengeti were also related to grass mineral content (McNaughton 1990). In this case, the important elements identified were calcium, copper, nitrogen, sodium, zinc and also, for lactating females and growing young, magnesium and phosphorus. In South Africa, Ben-Shahar & Coe (1992) showed that the movements of migratory grazers were related to monthly variations in the nitrogen and phosphorus content of grasses. Thus the enclosure of wildlife within relatively small national parks may restrict their opportunity through migration to acquire adequate major and trace elements.

Soils in the area of the Kenyan Rift Valley around Nakuru have long been associated with mineral problems including copper deficiency in wheat (Pinkerton 1967) and copper and cobalt deficiencies in cattle (Hudson 1944; Howard 1970). Lake Nakuru National Park has been

**Table 5.** *Copper concentrations in animals ($\mu mol\ L^{-1}$ blood plasma)*

| | | Mean | Range | n |
|---|---|---|---|---|
| *Impala* | | | | |
| Lake Nakuru N.P. | 1986 | 11.0 | 4.0–18.9 | 25 (D) |
| | 1987 | 14.2 | 4.8–29.7 | 7 (D) |
| All Kenya | | 19.8 | | 81 (S) |
| | | 20.3 | | 21 (D) |
| *Waterbuck* | | | | |
| Lake Nakuru N.P. | 1987 | 13.4 | 11.2–17.0 | 3 (D) |
| *Black Rhino* | | | | |
| Solio W.R. | 1987 | 16.9 | 3.8–24.6 | 14 (D) |
| Zimbabwe | | 25.6 | 19.2–36.4 | 20 (D) |
| *White Rhino* | | | | 81 (S) |
| Solio W.R. | 1987 | 20.8 | 18.6–23.1 | 21 (D) |

D, drug immobilized; S, shot.
From Maskall & Thornton (1991).

associated with suspected copper deficiencies in waterbuck (*Kobus defassa*) and impala (*Aepyceros melampus*) since the early 1980s. A low copper status of impala in the Park was reported by Maskall & Thornton (1991) based on concentrations of copper in blood plasma (Table 5). This was attributed to a high dietary intake of molybdenum which can interfere with the utilization of copper in ruminant animals (Underwood 1977). The mean molybdenum contents of plants in Lake Nakuru National Park (Table 3) are generally in excess of the $2\,\mu g\,g^{-1}$ level considered by Thornton (1977) to be sufficient to induce copper deficiency in domestic ruminants. In summary, the low copper status of impala at Lake Nakuru National Park is related to the low copper status of soils combined with an elevated soil pH, particularly in the solonetz soil, which results in enhanced molybdenum uptake into plants.

Molybdenum-induced copper deficiency has been reported in other wild animals including Grant's Gazelle (*Gazelle granti*) from the Kenyan Rift Valley; in this case the plant molybdenum content ranged from $0.5–5.6\,\mu g\,g^{-1}$ (Hedger *et al.* 1964). Plant molybdenum concentrations of less than $2\,\mu g\,g^{-1}$ were considered contributory to copper deficiency in moose (*Alces alces gigas*) in Alaska (Kubota 1974; Flynn *et al.* 1977*a*,*b*). In San Diego Wild Animal Park, USA, hypocuprosis in several exotic species was associated with alfalfa with a molybdenum content of $11–16\,\mu g\,g^{-1}$ (Nelson 1981). On the basis of these data, molybdenum concentrations in *Sporobulus spicatus* at Amboseli National Park, which have an average of $86\,\mu g\,g^{-1}$ (Table 4), are probably capable of inducing copper deficiency in certain wild ruminant species.

The high molybdenum content of solonchak soils at Amboseli could also affect animals which directly ingest earth at salt licks. In some cases, wildlife species preferentially ingest sodium-rich soils perhaps as a response to sodium deficiency (Fraser *et al.* 1980). Mule deer in Colorado were estimated to be ingesting between 8 and 30 g of soil per day from deliberate consumption of earth (Arthur & Alldredge 1979). In domestic ruminants soil ingestion has been shown to increase cobalt and selenium status (Healy 1973; MacPherson *et al.* 1978) although copper absorption and utilization can be inhibited (Suttle *et al.* 1984). However, little is known at present of the effects of earth eating behaviour in wild animals in terms of nutritional benefits or otherwise.

## Conclusions

Broad variations in the concentrations of some trace and major elements in soils between the wildlife conservation areas studied are attributable to differences in soil parent material. However, pedogenic processes influence the distribution in soil profiles of trace and major elements, of which the latter can affect soil pH and trace element uptake into plants and animals. At Lake Nakuru National Park, the process of sodication at the lake margins has produced an alkaline solonetz soil which has particularly low concentrations of several nutritionally essential trace elements in the surface horizon. Salinization processes in an alkaline solonchak at Amboseli National Park have contributed to a marked accumulation of molybdenum, sodium, potassium, calcium and magnesium in the surface horizon. At the Aberdares Salient, apparent mobilization of trace elements in a humic nitisol is associated with eluviation and leaching processes. Trace elements are accumulated in the A horizon in two andosols and an ando-humic nitisol possibly in association with organic matter. In vertisols at Lewa Downs Wildlife Reserve and Amboseli National Park, the relatively constant concentrations of trace elements throughout the A and B horizons may be linked to homogenization of the profile by self-swallowing processes.

The conservation of wild animals and the associated tourism industry represent a significant source of income for many countries in the developing world and particularly in Africa. There is increasing evidence to suggest that the seasonal movements of grazing wildlife in Africa are related to changes in mineral status of forage species. The enclosure of wild animals within relatively small, enclosed National Parks may restrict their opportunities through migration to acquire an adequate intake of major and trace nutrients. In such cases, the health of the animal population, which may include rare or endangered species, depends on the ability of the conservation area to supply sufficient minerals. This in turn is influenced by the concentrations and bioavailabilities of major and trace elements in soils and the local vegetation and climate. The pressure on land resources for agriculture and settlement in developing countries increases the likelihood that conservation areas will be located on land of marginal quality. This study has shown that the presence of sodic and saline soils of low agricultural quality in conservation areas may have deleterious effects on the health of particular species. At Lake Nakuru National Park, the presence of solonetz soils of low trace element status and high pH lead to an elevated molybdenum content of plants and a low copper status in impala due to excess dietary molybdenum. At Amboseli National Park, the high pH and molybdenum content of a solonchak have resulted in elevated molybdenum concentrations in plants which are capable of inducing copper deficiency in grazing ruminants. The incidence of molybdenum induced copper deficiency in livestock can be alleviated through supplementation with mineral mixes. Additional major and trace elements could be provided to wild animals in areas of low mineral status by addition of mineral supplements to salt-lick soils.

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