CHAPTER 10

PLANT-SOIL ASSOCIATIONS

Abstract

Maize seedlings were grown in chromium-rich soils collected from an ultramafic catena. The seedlings showed typical symptoms of Ni and Cr toxicity. The response of maize plants suggested that accumulation of heavy metals, notably Cr and Ni, by indigenous plants could be possible. To investigate this hypothesis, 20 indigenous plant species were sampled along 13 points of the ultramafic catena. Plant material and soil samples were analysed with standard analytical methods to determine the concentrations of 33 elements, including several heavy metals. Twelve rock types of the Sekhukhuneland Centre of Plant Endemism were also analysed to determine whether a chemical relationship exists between the rocks of the study area and serpentinite. Nine SCPE endemics, three SCPE near-endemics, and eight wide-spread species were used for the analyses. None of the investigated taxa were clear hyperaccumulators of Cr or Ni, but plants of seven indigenous species accumulated more than 1 000 mg/kg of Fe and Al. The accumulation of high concentrations of heavy metals was mostly found in species that were common on and of the ultramafic soils, but included one SCPE near-endemic and one SCPE endemic form. Three of the hyperaccumulators belong to the Asteraceae.

10.1 Introduction

The past twenty years have witnessed an extraordinary increase in the interest of plants that hyperaccumulate heavy metals on ultramafic substrates such as serpentinite. These unusual species have found a ready application in such diverse fields as geobotany, phytochemistry, archaeology, mineral exploration, ecology, phytoremediation and phytomining (Cole & Le Roex 1978; Brooks 1998).

Serpentinite and other ultramafic rocks are rich in ferro-magnesium minerals. They outcrop as raised segments of a continent's crust and constitute a small proportion of the earth's land surface (Brooks 1987). Soils formed from ultramafic rocks have unusual characteristics, and are rich sources of heavy metals especially nickel (Ni), chromium (Cr), manganese (Mn) and iron (Fe) (Wild 1978). The remaining soil matrix is largely composed of relatively inert ferric and chromic oxides. In addition, calcium (Ca) deficiency and toxic levels of magnesium (Mg) in these soils can create an unfavourable Mg:Ca ratio which may lead to poor Ca assimilation. It should be noted that minerals such as arsenic, serpentine and gypsum have importance as constituents of ultramafic soils (Wild 1978).

On serpentinite the adverse effect of heavy metals is enhanced by the low levels of calcium in relation to magnesium, the lack of organic matter, and poor physical texture of the soil (Wild 1974a; Wild 1974b; Brooks & Yang 1984; Hughes & Noble 1991; Roberts & Proctor 1992). The poor soil structure and restricted soil depth, reduces root penetration and water content, and contributes to water stress in plants. As a result, serpentineferous areas have several endemic species adapted to high concentrations of heavy metals and generally adverse edaphic conditions (Proctor 1971; Proctor & Woodell 1975; Morrey *et al.* 1989; Roberts & Proctor 1992; Freitas & Mooney 1996).

Globally about six plant families are known to include more than ten species able to hyperaccumulate Ni (Borhidi 1998). Two of these families, Brassicaceae and Euphorbiaceae, have more than 80 plant species that can hyperaccumulate heavy metals (Borhidi 1998). The remaining four families, namely the Asteraceae, Buxaceae, Flacourtiaceae and Rubiaceae, have less than 30 hyperaccumulator species,.

In Sekhukhuneland, some species from the Araceae, Euphorbiaceae and Vitaceae exhibit a specific relationship with certain heavy metal soils (Siebert 2000). None of these species have been tested for the accumulation of heavy metals. One of the hypotheses suggested by Siebert (1998) was that indigenous plants from the Sekhukhuneland region, and notably some of the taxa endemic to the region, could possibly accumulate Cr.

There are conflicting views concerning the uptake and translocation of Cr (VI) in plants (Kimbrough *et al.* 1999). Wild (1974b) reported considerable uptake of Cr by the serpentine endemics, *Dicoma niccolifera* and *Jamesbrittenia fodina* (*Sutera fodina*), though this was subsequently ascribed to contamination (Cr on leaf surface) (Brooks & Yang 1984). Other plants that have been identified as Cr accumulators are *Sporobolus pectinatus* and a species of *Sutera* (Morrey *et al.* 1989).

Chromium is the seventh most abundant element on Earth (Katz & Salem 1994). It occurs in several oxidation states, with the trivalent and hexavalent states, namely Cr (III) and Cr (VI), being the most stable and common in terrestrial environments. Chromium can be both beneficial and toxic to animals and humans depending on its oxidation state and concentration (Kimbrough *et al.* 1999). At low concentration, Cr (III) is essential for animal and human health. Cr (VI) is a potent, extremely toxic carcinogen and may cause death to animals and humans if ingested in a large dose (Nriagu & Nieboer 1988).

There is a notable dearth of information in the literature pertaining to Cr uptake, toxicity, translocation, soil/plant relationships and effects on plant growth. Clearly these are aspects that require substantial investigation, specifically for regions such as Sekhukhuneland, where the soil concentrations of Cr and Ni are in certain areas respectively 500 and 60 times higher than the maximum permissible soil concentration of trace elements allowed in legislation and guidelines for South Africa (Steyn *et al.* 1996).

Very little is known about the uptake of Cr by plants. Nowhere in the world is it as abundant in natural soils as in the SCPE. This chapter includes discussions on the occurrence and geobotany of a selected number of plant species growing in the vicinity of chromitite outcrops in the SCPE. It also touches on a specific group of metals that are abundant in the ultramafic soils of the Rustenburg Layered Suite.

Footnote

Methods for this chapter are presented in Chapter 3, 3.2 Plant and soil analyses.

10.2 Maize seedlings grown in ultramafic soils

10.2.1 Background

This section deals with the growth limiting effect that ultramafic soil samples from chromitite outcrops in the SCPE have on maize seedlings. This effect is presumably caused by the toxicity of the soil samples. The limiting factor is measured as the average biomass production of maize seedlings grown in toxic soils (Table 29) as a percentage of the average biomass production of maize seedlings grown in the control soils.

The levels of N, P, S, Mg, Ca, Ni and Cr was determined in the roots and leaves of maize grown on metalliferous soil samples from a chromitite outcrop in the SCPE. The heavy metal concentrations in plant tissue tested for, is known to induce growth limiting effects on maize at certain critical levels (Cooper 1986). These levels were determined as the concentration of elements present in the maize when growth of roots and leaves becomes restricted in containers with Cr rich soils, compared with maize grown in containers with neutral quartzite sand as a control.

The objective of the experiment was to test applicability of results found by Cooper (1986) with regards to Cr toxicity, before more expensive methods were used to determine absorbtion and accumulation of heavy metals such as Cr and Ni in indigenous plants from Sekhukhuneland

10.2.2 Results and discussion

Root development of maize seedlings grown in the soil samples from the chromitite outcrop was stunted during the first two weeks, but the growth rate increased over time when compared with control plants (Figure 17; Table 30). As the soil became less toxic, and Cr and Ni were translocated from the roots to the leaves, the leaves showed a decrease in their average biomass production (Table 30). During the first two weeks the effect of Cr and Ni toxicity was minimal in the leaves of maize seedlings grown in the heavy metal soil. Plants grown in the heavy metal soil were dark green and indistinguishable from control plants. From 3 to 4 weeks leaf growth became stunted (Figure 17) and developed a degree of chlorosis and purpling (Figure 18).

Ultramafic soils from chromitite outcrops in Sekhukhuneland proved to be toxic to maize. Apart from severe stunting that occurred in leaf growth, the most important abnormalities were interveinal chlorosis and purpling, especially on newly extending leaves. Interveinal chlorosis (longitudinal striping of maize leaves) and leaf purpling was visible on plants grown in the ultramafic soils of the chromitite outcrop (Figure 18). Control plants in the quartzite soil had no such symptoms. This was clear evidence of the toxic effect that Ni has on maize. Interveinal chlorosis of leaves resulted from uptake of Ni in leaves (Table 31; Figure 19). The chlorosis was similar to that described specifically for Ni toxicity where Ni was translocated to leaves (Hunter & Vergano 1952). Leaf purpling is specific to and the result of Cr accumulation in leaves (Cooper 1986). Foliar analysis supported the hypothesis, as chlorotic and purple leaves showed higher levels of Ni and Cr than leaves of plants grown in the control soil (Table 31; Figure 19).

Chromium was accumulated more in the leaves than Ni (Figure 19). More Ni accumulation took place in the roots (Figure 19). Overall accumulation of both metals was more or less restricted to the roots, a phenomenon previously recorded (Cary *et al.* 1977). Overall very low concentrations were recorded in the leaves and roots. Chromium and Ni concentrations in the plant tissues decrease with time as the heavy metal concentrations in the root environment become depleted as a result of plant growth and uptake (the "plant size:heavy metal concentration" ratio increases). The same tendencies with regards to low levels of Cr and Ni accumulation were observed in indigenous grasses (Poaceae family) growing naturally at the site where the soil samples were collected (Table 32; Figure 20). However, Fe and Al were accumulated extensively.

Maize seedlings in this experiment (Table 31) showed similar Cr and Ni concentrations in their leaves to those of eleven tested vegetable crops (Zayed *et al.* 1998) and considerably lower concentrations in their roots. The wild grass species analysed (Table 32) also showed higher Cr and Ni concentrations in their leaves and lower concentrations in their roots than the vegetable crops analysed by Zayed *et al.* (1998). However, two of the grass species accumulated Al and Fe at levels above 1 000 mg/kg. This will be discussed in the next section.

During the first two weeks nutrient levels of N, P and S in roots and leaves of maize seedlings were high (Figure 21). These levels decreased substantially in the third week and kept on declining in the fourth week. Overall the nutrient levels were higher in the leaves than the roots. Mg and Ca levels of the roots and leaves of the seedlings remained more or less constant throughout the four weeks (Figure 21). No leaf edge splitting was recorded, indicating that there was no Ca deficiency in the plants (Cooper 1978; Kawaski & Moritsugu 1979). The Mg:Ca ratio in the plant material is low, namely 1:1.35 (Table 31), whereas the Mg:Ca ratio in the soil samples is high, namely 1:0.45 (Table 31). Nutrient levels in the indigenous grasses varied and no distinct patterns could be observed (Figure 22). The Mg:Ca ratio for the indigenous grasses is approximately 1:2.

A possible external factor that might have influenced the results obtained in the maize experiment is that the control soil was sterilised, hence also without any arbuscular mycorrhiza. This means the experiment could have been influenced by natural occurring mychorrhiza in the chromitite outcrop soil samples. Experiments have shown that maize can grow in heavy metal soil due to selective immobilization of heavy metals within the root tissues containing fungal cells of arbuscular mycorrhiza (Kaldorf *et al.* 1999) which serve as an exclusion mechanism.

10.3 Natural vegetation on ultramafic soils

10.3.1 Background

As would be expected in a sub-continent with about 30 000 native plant species, southern Africa proved to have its own unique serpentiniferous flora. The Great Dyke of Zimbabwe and the Barberton Sequence of South Africa harbour a number of plant species that hyperaccumulate Ni. Wild (1970) and Brooks & Yang (1984) recorded several hyperaccumulators of Ni on the Great Dyke. Morrey *et al.* (1992) reported hyperaccumulation of Ni by several members of the Asteraceae from the Barberton Sequence in Mpumalanga. One of these species, *Berkheya coddii*, is renowned for its ability to hyperaccumulate Ni. Its ability to accumulate Ni in large quantities was first reported by Morrey *et al.* (1989) and its economic viability in phytoremediation was investigated by Anderson *et al.* (1995).

This section focuses on the potential heavy metal accumulators of the eastern Rustenburg Layered Suite (RLS), a part of the Bushveld Complex that is one of the world's largest ultramafic complexes. The work conducted in this section is similar to the approach followed by Brooks & Yang (1984) on the Great Dyke, Zimbabwe, and by Cole (1992) on the ultramafics of the South African Lowveld. The RLS underlies the Sekhukhuneland Centre of Plant Endemism in Mpumalanga and the Northern Province, South Africa (Siebert 1998) (Figure 1). It shows considerable diversity in habitat and soil chemistry (Land Type Survey Staff 1989; Visser *et al.* 1989), and supports a highly diverse and unusual type of Mixed Bushveld (Acocks 1953) flora of more than 2 000 angiosperm species and infraspecific taxa (Siebert 2000; Chapter 11). Siebert (1998) recognised approximately 50 taxa as being endemic to the ultramafic substrates of Sekhukhuneland. These substrates are classified as serpentine in botanical literature (Knowles & Witkowski 2000).

The ultramafic soils analysed in this study are representative of the regions where the local flora exhibit high degrees of endemism. This thesis is a preliminary investigation into the heavy metal soils of the Critical Zone of the RLS, the richest area in both plant endemics (Siebert 1998) and heavy metals (Schurmann *et al.* 1998). The purpose of this investigation was to determine whether the concentrations of heavy metals from soils in the SCPE are comparable with other serpentineferous soils in the world. This forms the basis to determine whether the plant taxa on heavy metal outcrops in the SCPE are accumulators or excluders (as defined by Baker (1981)) of heavy metals. One of the aims of this section is to stimulate further research on heavy metal soils and its associated vegetation, as more information on the concentrations of trace elements in such soils is much needed (Steyn *et al.* 1996). It is hoped that this contribution may stimulate further scientific research and commercial use of plants growing on the heavy metal outcrops of the SCPE.

10.3.2 Results and discussion

The results and discussion of this section is divided into five subheadings. The rocks of the study area are discussed followed by the soils, the catena, the plants and concludes with the plant-soil associations.

10.3.2.1 Rock analyses

Rocks were analysed and sorted according to their Mg:Ca ratio (Figure 23), and were ordered according to this relationship in the data tables (Appendix 2). Rock types presented in the graphs were also displayed in this order to standardise the x-axis of the figures (Figure 26), with Groen Valley serpentinite left (A, Mg:Ca ratio = 34.52 Mg : 1 Ca) and Leolo Mountain norite right (M, Mg:Ca ratio = 1 Mg : 5.56 Ca). Exposed rocks of serpentinized harzburgite, magnetitite and chromitite showed similar Mg:Ca ratios and high chromium/nickel concentrations, as was found in the serpentine control Groen Valley, Barberton Greenstone Belt (Balkwill & Burlin 1995). The serpentine related rock types are typical of the Critical Zone of the Rustenburg Layered Suite.

When the chemical composition of the rock data are compared, the following is evident from the gradient (Appendix 2):

- Cr, Ni and Mg are highest in the serpentinite, serpentinized harzburgite, magnetitite and chromitite—in addition the magnetitite shows high Zn concentrations;
- Ti, V and Fe are highest in magnetite, chromate and black sand in dongas;
- K is highest in Getlane shales and Burgersfort pyroxenite;
- Cl is highest in Burgersfort pyroxenite and Roossenekal norite;
- P is highest in Olifantspoortjie pyroxenite and diabase dykes – in addition Cu is highest in diabase dykes;
- Ca is highest in Olifantspoortjie pyroxenite, concresions of the Steelpoort Valley, and Leolo and Roossenekal norite – in addition Leolo norite is rich in Na;
- Si is highest in quartzite sills.

These heterogeneities in element concentrations across the range of sampled rock support the diverse range of plant communities reported on in Chapter 4, 4.3 Hierarchical classification. From here onwards, focus will be on the rock associated with the transect/catena (Figure 24) that was sampled for the study of the plant species that grow abundantly on heavy metals soils of the SCPE. Note that there is a difference between the gradient obtained here and the soil catena discussed in section 10.3.2.3.

10.3.2.2 Soil analyses

A profile of the study site (catena) on the Critical Zone of the RLS is given in Figure 24. A transect of the catena can be divided into a floodplain (A & B), dongas or erosion gulleys (C, D & K), slopes (E–I), and a chromitite outcrop (J, L & M). Soils most frequently associated with the Critical Zone are melanic A-horizons over pedocutanic/carbonate B-horizons such as the Bonheim and Steendal forms, and ortic A-horizons over hard rock/lithocutanic B-horizons such as Mispah and Glenrosa forms. Soil samples from these regions were analysed and described as follows:

- Floodplain soils occur on the wide alluvial flats where they drain the areas between the norite and pyroxenite hills (A & B). In places these soils may overlie the Merensky and Bastard Reefs, including magnetitite outcrops (B). These landforms experience periodic local flooding during the rainy season. The profiles are deep (> 1.5 m), and can vary from black to dark brown, and may show characteristics of vertisols. Texture of the surface soil is a medium clay that gradually increases to a medium to heavy clay in low-lying areas, or adversely decreases to a medium to heavy loam on more raised areas. The soil layer where water collects during the wet season, is usually underlain by silica concretions.

- The soils of lower and footslopes can either be shallow or very stony and overlie partially weathered ultramafic rock, or moderately deep and depositional with stony profiles. The shallow soil type occurs directly at the foot of mountains and hills (E & F). These soils overlie exposed rock. They are black or dark brown, with a loam surface grading and clayey subsoil. The deeper depositional soils occur below raised areas in the floodplains (F). The raised areas (G) occur where the alluvium overlie rock outcrops. Gravel and stone are common throughout the profile. Soils are usually dark brown clays. Small siliceous nodules often occur in the subsoil. Below the hills natural erosion occurs (C & D). These soils lie within the floodways of drainage lines. The bottoms of these dongas are typically shallow and overlie gravel and stone. The profile of the soil on the raised sides is deep black or brown cracking clays that are poorly structured.

- Upper slopes and crests (H & I) of hills and mountains, and to some extent raised areas in the floodplains (B), overlie weathered ultramafic rock. They are typically shallow and extremely rocky. The soil texture is predominantly loam on the surface and has a light clay subsoil. Soil colour varies from reddish-brown to brownish-black. On the hills and mountains, narrow alluvial drainage flats occur (K). During the rainy season these soils become eroded due their weak structures. These landforms are basically landfills and are similar to the soils of the floodplains, but not as well developed. Outcrops of chromitite can occur on the crests and upper slopes of hills and mountains (J, L-M). These soils are extremely shallow (< 30 cm) with the bulk of the profile comprised of freshly weathered Cr, Ni and Fe ore, which mask the diffuse change to the parent material.

When the serpentine characteristics of the soils along the catena are compared, topographic positions J, K and M (chromitite outcrop) proved to be most closely related to serpentine, namely with low nutrient levels, high heavy metal levels and a high Mg:Ca ratio (Figure 25; see stippling for catena). Topographic positions E, F, G and H (hill slope) are least related to serpentine, and are possibly more related to the soils of the dolomites of the adjacent Transvaal Sequence. The valleys and erosion gulleys are intermediate between the outcrop and the hill slope.

Diagnostic metals for the soils of the valley and erosion gulleys are Cu, Mn and Ti and include other diagnostic elements, namely S, Cl and Si (Appendix 3; Table 33). Chromitite outcrop soils is characterised by Cr, Ni, Mo and Zn, which are relatively abundant. The valleys, erosion gulleys and chromitite outcrop soils can be distinguished from the mountain slope soils by high concentrations of metals, namely Co, Fe and V, and high levels of Mg (Appendix 3). The chemical composition of the soils on the mountain slope is different in that it has high concentrations of Ca, K, Na and P, and metals such as Al and Pb are abundant.

Scatter diagrams of selected serpentine related chemical attributes were plotted to determine the relationship between heavy metal concentrations, Mg:Ca ratios and nutrient levels for rocks and soils in the study area (Figures 26 & 27):

- *Nutrient levels (%) vs metal concentrations (mg/kg)*. For both the rock and soil samples the metal concentrations decreased as nutrient levels increased. This tendency relates directly to rocks with high heavy metal concentrations, because these rocks have lower levels of other elements per square meter of solid rock.

- *Metal concentrations (mg/kg) vs magnesium-calcium ratio (1Mg:xCa)*. The tendency in both rocks and soils is that of increasing metal concentrations with increasing Mg levels. This is best explained by the chemical composition of the ultramafic rocks. Soils in close proximity to serpentine related ultramafic rocks will exhibit the same Mg-heavy metal proportion.

- *Magnesium-calcium ratio (1Mg:xCa) vs nutrient levels (%)*. Rock and soil analysis show results that are not similar. Rocks show a slight positive, and soils a strong positive relationship between Mg:Ca ratios and nutrient levels. Ca-rich ultramafic soils are poor in nutrients, but in comparison with Mg-rich, serpentine-related substrates they are nutrient rich, hence the strong positive relationship. However, the rock samples are not all ultramafic and some have high Mg and high nutrient levels and others have high Ca and low nutrient levels. This gives rise to a weak positive relationship.

10.3.2.3 Catena analyses

Scatter diagrams of heavy metal, nutrient and Mg/Ca concentrations were plotted on the same y-axis as the topographic positions (metres above valley bottom) of the catena (Figure 25). It is evident that nutrient concentrations are the highest on the mountain slope (E–H). The higher nutrient concentrations occur on the mountain slope, because the rock of the chromitite outcrop is not fully weathered into minerals and the nutrients in the valley has been eroded away with the topsoil. Metal concentrations are highest at positions B, J, L and M and these areas are located above chromitite and magnetitite outcrops which are only partially weathered. The Mg/Ca ratio is lowest at positions E–I along the catena. These areas are also rich in Ca which it obtained from the underlying norite mother material.

Soils from 13 sites (Figure 24) along a catena/transect have been analysed (Appendix 4) to compare specific element levels in the local soils with those of serpentineferous areas in South Africa (Table 34) and the world (Table 35). In the soils of the catena, levels of pH vary from 6.67 to 7.84, total Ni from 81 to 1 133 μg/g, total Cr from 479 to 178 020 μg/g, total Mg from 6.44 to 23.44 %, total Ca from 5.61 to 18.53 % and the Mg:Ca ratio from 0.23 to 2.14 (Table 36).

On a local level (Table 34), the Mg/Ca ratio of Sekhukhuneland soils is much lower than that of serpentineferous areas elsewhere in Mpumalanga (Barberton) (Morrey *et al.* 1989). This is ascribed to the much higher Ca levels in the soils (and rocks) of Sekhukhuneland. K and N levels in the Sekhukhuneland soils are up to twice as high, Na levels are 10 to 20 times as high and C levels are more than twice as high than those measured for serpentines. Minimum levels of Cr and Ni concentrations in the Sekhukhuneland soils are two and 20 times lower respectively. Maximum levels of Ni in the Barberton serpentines are nearly four times higher than what was recorded for the Sekhukhuneland soils, but Cr levels are nearly 50 times higher in the Sekhukhuneland soils. Serpentinite soils therefore only have extreme concentrations of Mg and Ni which are higher than those of the Sekhukhuneland soils. In addition the pH of the Mpumalanga serpentinites are lower than that of the Sekhukhuneland soils.

On a world scale of selected ultramafic sites (Table 35), the Sekhukhuneland soils have low maximum Ni levels, but extremely high maximum levels of Cr. Mg levels in the Sekhukhuneland soils are average, but the Ca levels are two times higher than the average. The Mg:Ca ratio is therefore lower than that of serpentineferous soils, but higher than that of polluted Canadian soils.

10.3.2.4 Plant analyses

The Great Dyke is probably the most well-known serpentineferous area in southern Africa. Average levels of element accumulation by plants of Sekhukhuneland and the Great Dyke (Brooks & Yang 1984) differ in that eight times higher levels of Ni, as well as higher levels of Fe and Mn, were recorded in species of the Great Dyke (Table 36). Six times higher levels of Mg were also recorded for plants of the Great Dyke (Table 36). On the other hand, two times higher Cr levels and nearly three times higher Al levels were recorded for Sekhukhuneland soils. Sekhukhuneland soils have 0.5 times higher Ca levels in plant material.

Twenty plant species were sampled from the catena and analysed, with five dicotyledon species proving to be hyperaccumulators of heavy metals (Appendix 4). Hyperaccumulation was restricted to Fe and Al. *Pterothrix spinescens*, *Jamesbrittenia atropurpurea*, *Dicoma gerrardii*, *Berkheya insignis* and *Euclea linearis* accumulated levels above 1 000 mg/kg of Al and Fe in their leaves, roots and stems. To this list can be added the monocotyledons (grasses) *Diheteropogon amplectens* and *Heteropogon contortus* (10.2.2 Results) (Table 32). The highest levels were recorded in the roots of *Berkheya insignis*. Leaves with the highest Al and Fe levels belong to *Pterothrix spinescens*. Eight species also showed levels of Fe and Al above 500 mg/kg, but below 1 000 mg/kg. These species are all potential hyperaccumulators of Fe and Al (Table 40). *Pterothrix spinescens* also had the highest concentrations of Cr of any plant parts (stem) that were sampled along the catena (420 mg/kg).

In a scatter diagram of the nutrient level versus the metal concentration of all plant material collected along the catena, it is shown that metal uptake increases as the nutrient uptake decreases (Figure 28). It is also shown that the metal concentrations in the plant material increases as the Ca in the plant tissues increases (Figure 28). Ca levels in the plant material was also related to high nutrient levels in the tissue, which probably relates to the mother material on which the species with high Ca levels grow (Figure 28).

A detailed analysis of serpentine associated chemical attributes in plant tissue indicated specific tendencies in each of the three major areas along the catena, namely eroded areas, hill slope and chromitite outcrop (Figure 29; Table 37):

- *Eroded areas.* Scatter diagrams of the Mg:Ca ratios, heavy metal concentrations and nutrient levels in the leaves and roots of species growing in the dongas (erosion gulleys) show tendencies similar to those of the catena as a whole. The only difference was observed in the Mg:Ca ratio versus heavy metal concentration of the root tissues. In this case metal concentrations increased as Ca levels decreased.

- *Hill slope.* Scatter diagrams of the Mg:Ca ratios, heavy metal concentrations and nutrient levels in the leaves and roots of species growing on the hill slope show different tendencies than the catena as a whole. The first difference was observed in the Mg:Ca ratio versus heavy metal concentration of the root tissue. In this case metal concentrations increased as Ca levels decreased. The second difference is found in the metal concentration versus nutrient level scatter diagrams of both the leaves and roots. In these diagrams the metal concentrations increased with those of the nutrient levels.

- *Chromitite outcrop.* Scatter diagrams of the Mg:Ca ratios, heavy metal concentrations and nutrient levels in the roots of species growing on the outcrop show similar tendencies than the catena as a whole. However, leaf tissue shows different tendencies. The Mg:Ca ratio versus heavy metal concentration of the leaf tissue shows an increase in metal concentration with an increase in nutrient levels. In the case of metal concentrations versus the Mg:Ca ratio, Ca levels decreased with increasing metal concentrations. Leaf tissue also exhibit decreasing Ca levels where nutrient levels are high.

10.3.2.5 Plant-soil associations

Soil nutrient levels plotted against plant nutrient levels, soil metal concentrations against plant metal concentrations and soil Mg:Ca ratios against plant Mg:Ca ratios, present graphs with different relations (Figure 30). The results were not expected, as levels in the soil should be reflected in the plant tissue. However, concentrations in plant tissue were related to positions along the catena. Plants growing on the more fertile mountain slopes have higher nutrient levels in their tissue compared to the plants of the eroded areas and the chromitite outcrop. The same trend was observed for the Mg:Ca levels with higher levels of Ca in plants growing on the Ca-rich slopes and higher Mg levels in the plants growing on the Mg-rich soils of the eroded areas and dongas. The scatter diagram of the heavy metal concentrations exhibits a completely different pattern than would be expected. Lower accumulation rates by plants at higher soil metal concentrations of the study sites indicate that these species are excluders. From this graph it is clear that the plants sampled for this study accumulate heavy metals when it occurs at approximately 20–25 mg/kg in the soil, but with increasing soil concentrations the levels in the plant tissue becomes lower and finally, the heavy metals are excluded.

At Cr concentrations of below 5 000 mg/kg in the soil, accumulation by plants in the eroded areas are the highest (Figure 31). This indicates that there are higher levels of available Cr in the dongas (erosion gulleys). Ni concentrations of 400 to 600 mg/kg in the dongas give rise to the highest levels of Ni accumulation by plants (Figure 31), probably also as a result of its availability in these areas.

	2 weeks	3 weeks	4 weeks
Mean leaf length %	97	89	77
Mean root length %	88	95	95
Mean leaf dry mass %	96	94	77
Mean root dry mass %	78	82	88

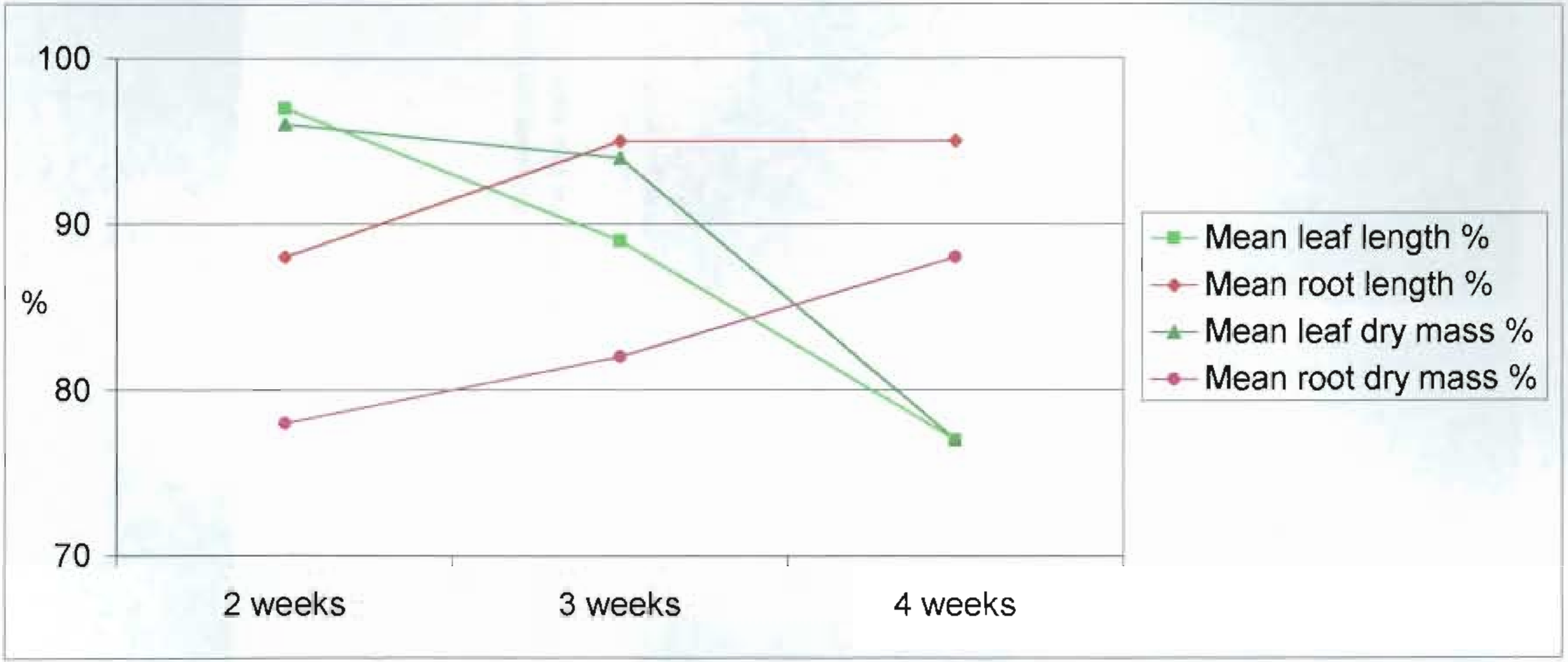


Figure 17 Average biomass production of the roots and leafs of *Zea mays* seedlings grown in an ultramafic soil mixture. The averages are expressed as a percentage of the control.

i). Eight seedlings per pot in quartzite soil (left) and chromium soil (right) after four weeks.

ii). Four seedlings per pot in quartzite soil (left) and chromium soil (right) after four weeks.

iii). Two seedlings per pot in quartzite soil (left) and chromium soil (right) after four weeks.

Figure 18 Interveinal chlorosis and leaf purpling in *Zea mays* as a result of Ni and Cr toxicity respectively (i-iii are different densities of seedlings).

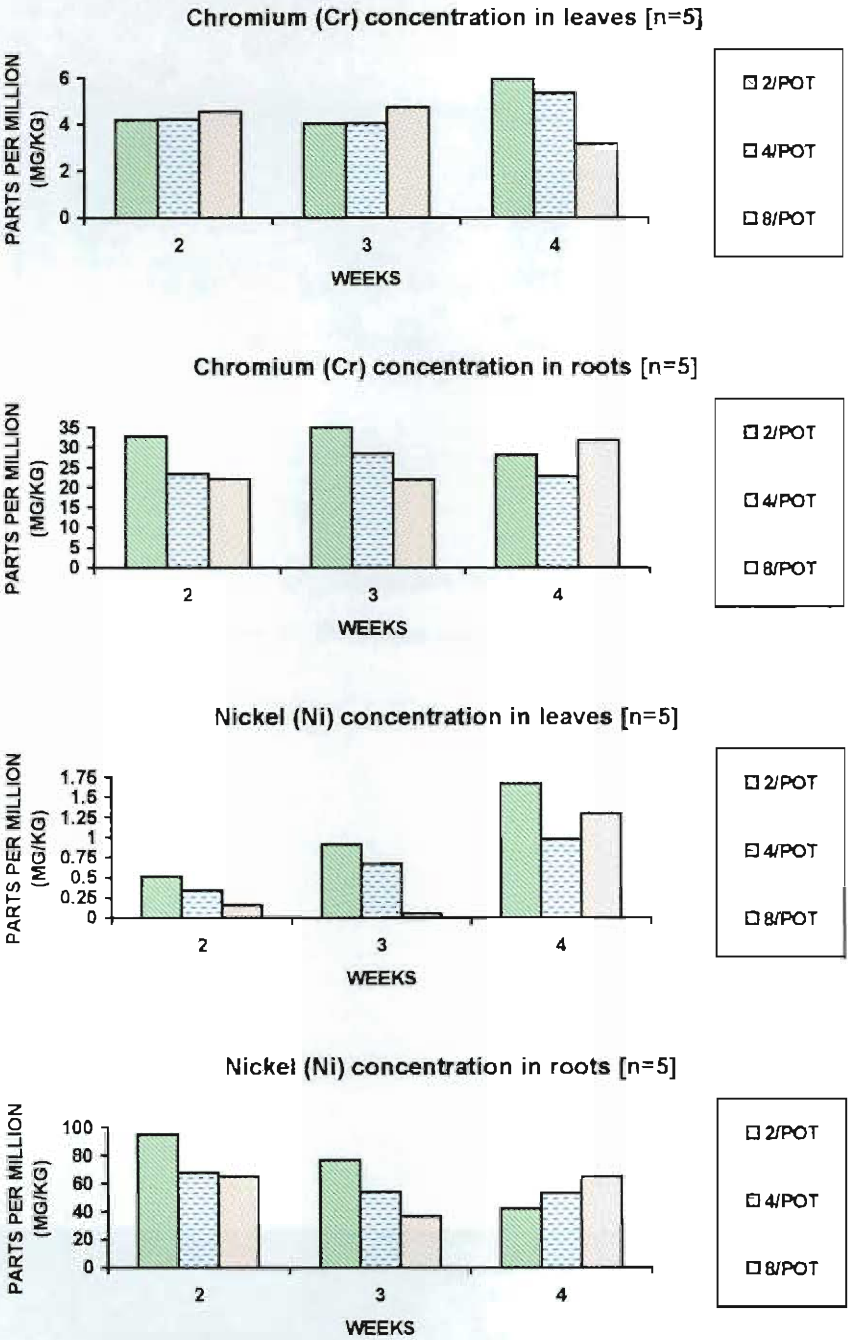


Figure 19 Heavy metal concentrations in the leaves and roots of *Zea mays* seedlings grown at different densities in a chromitite outcrop soil mixture for 2, 3 and 4 weeks respectively.

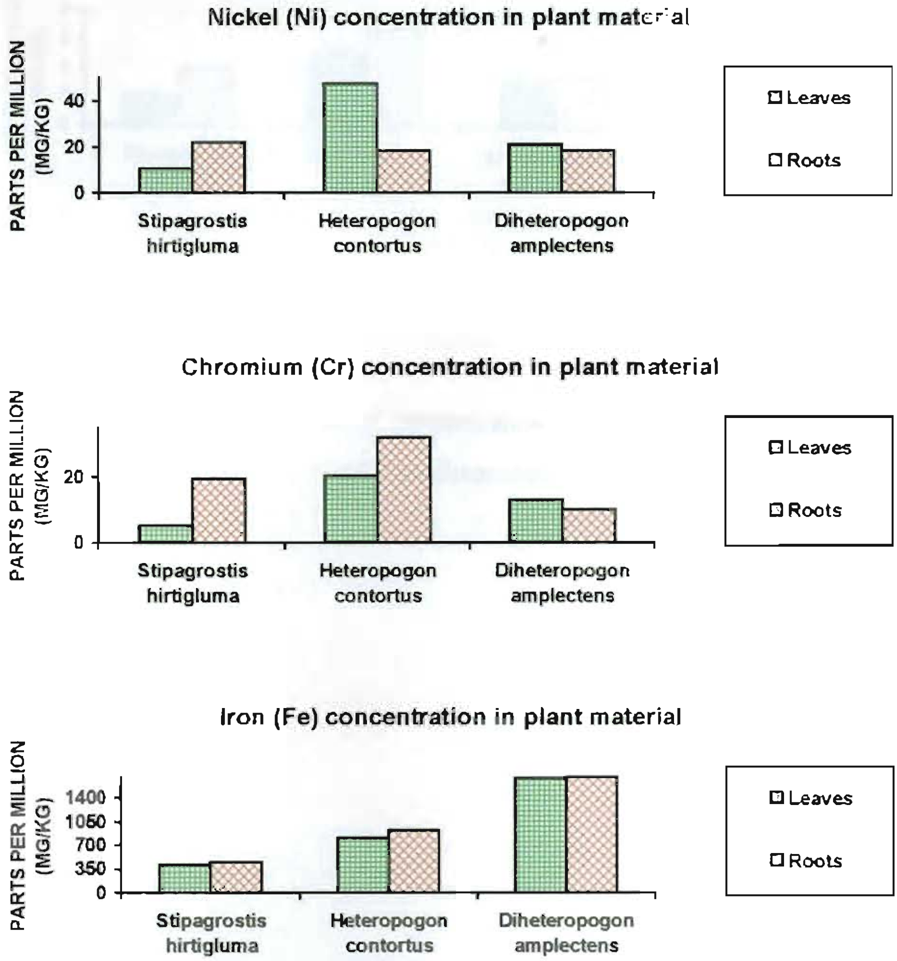
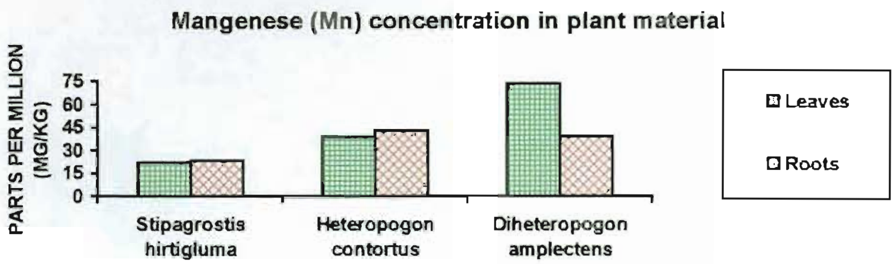
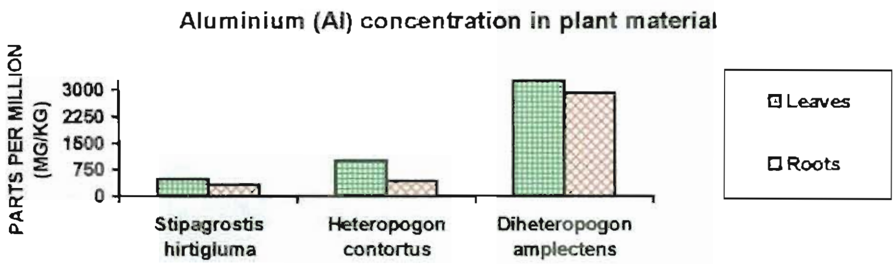


Figure 20 Heavy metal concentrations in the leaves and roots of three indigenous grass species growing naturally on chromitite outcrops.





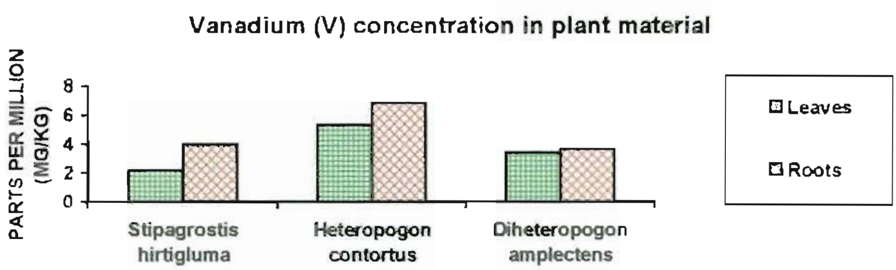


Figure 20 (continued) Heavy metal concentrations in the leaves and roots of three indigenous grasses growing naturally on chromitite outcrops.

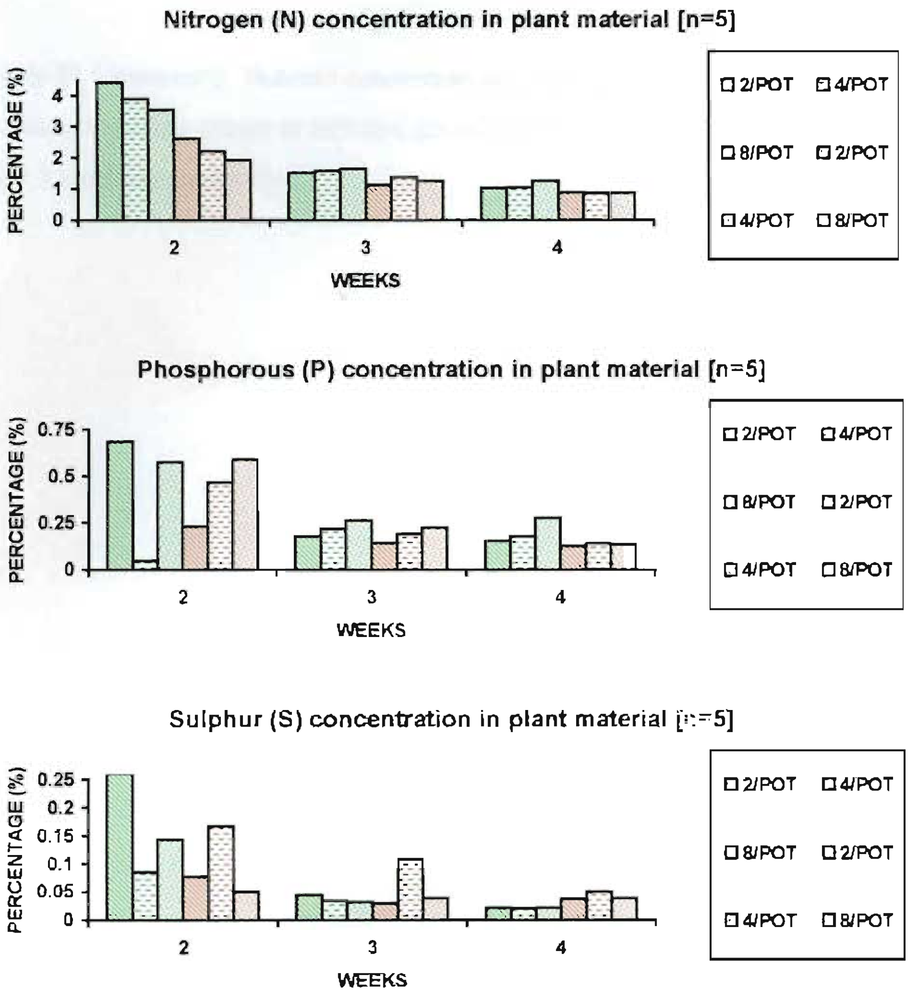
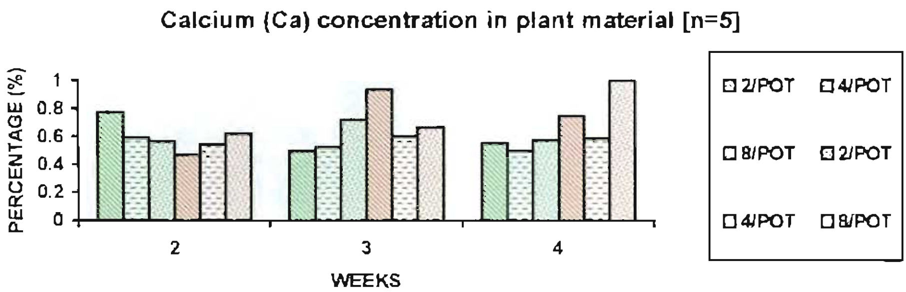


Figure 21 Nutrient concentrations in the leaves (green) and roots (brown) of *Zea mays* seedlings grown at different densities in a chromium outcrop soil mixture for 2, 3 and 4 weeks respectively.



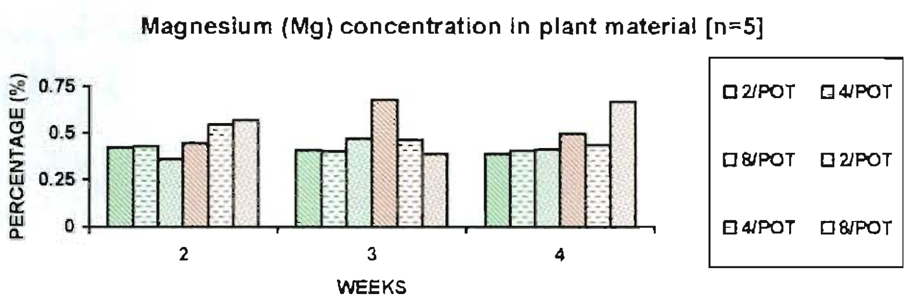


Figure 21 (continued) Nutrient concentrations in the leaves (green) and roots (brown) of *Zea mays* seedlings grown at different densities in a chromium outcrop soil mixture for 2, 3 and 4 weeks respectively.

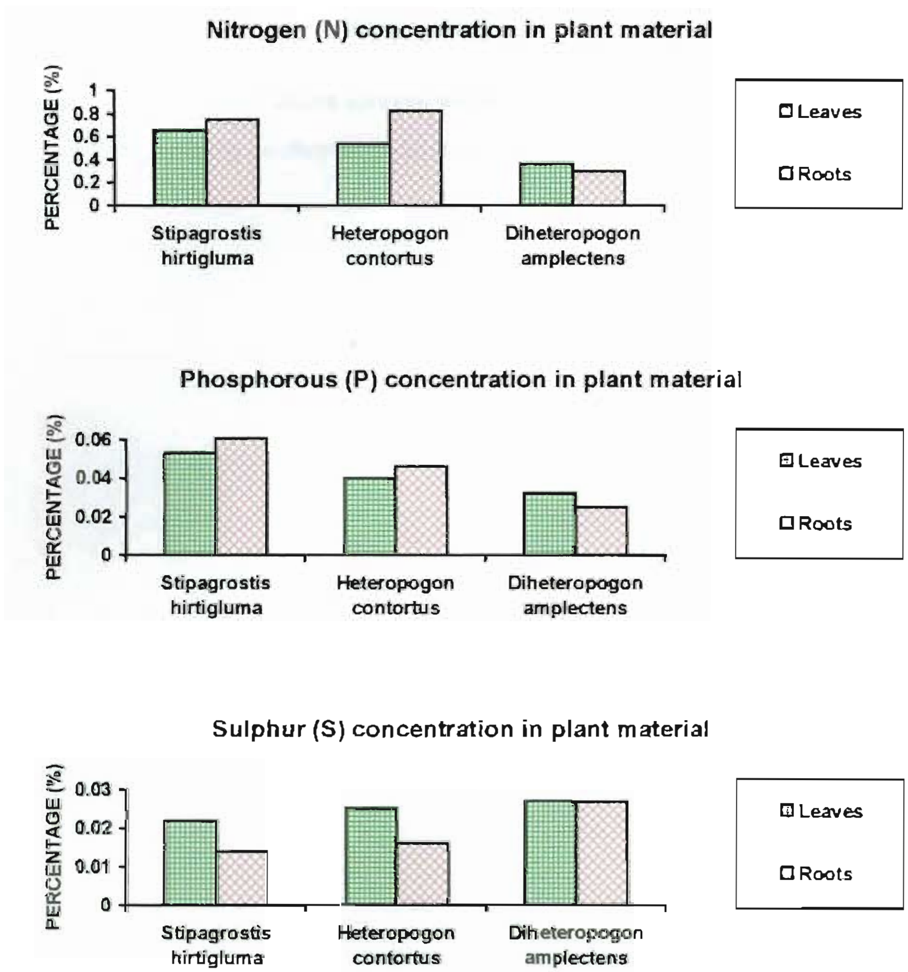
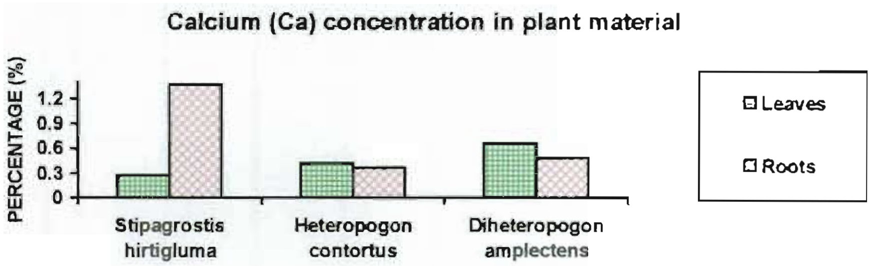


Figure 22 Nutrient concentrations in the leaves and roots of three indigenous grasses growing naturally on chromium outcrops.



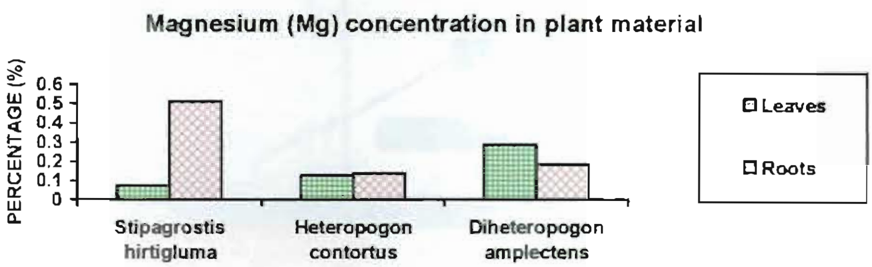


Figure 22 (continued) Nutrient concentrations in the leaves and roots of three indigenous grasses growing naturally on chromium outcrops.

	Mg:Ca Ratio
I	34.52
II	18.2
III	14
IV	9.84
V	3.66
VI	1.33
VII	1.3
VIII	1.13
IX	1.03
X	0.9
XI	0.47
XII	0.45
XIII	0.18

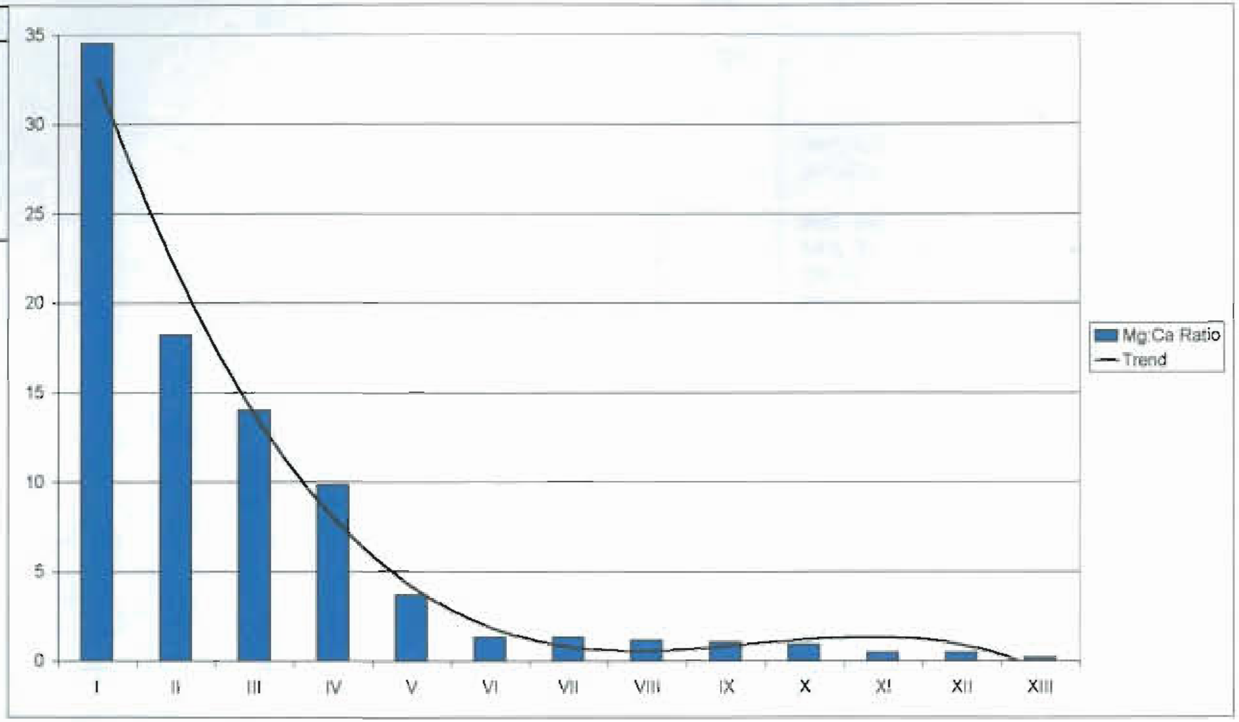


Figure 23 Analysed rocks were sorted according to their Mg:Ca ratio (as an idication of the serpentine gradient), with Green Valley serpentine left (A, Mg:Ca ratio = 34.52) and Leolo Mountain norite right (M, Mg:Ca ratio = 0.18). This gradient was used for the bar graphs in Appendix 2.

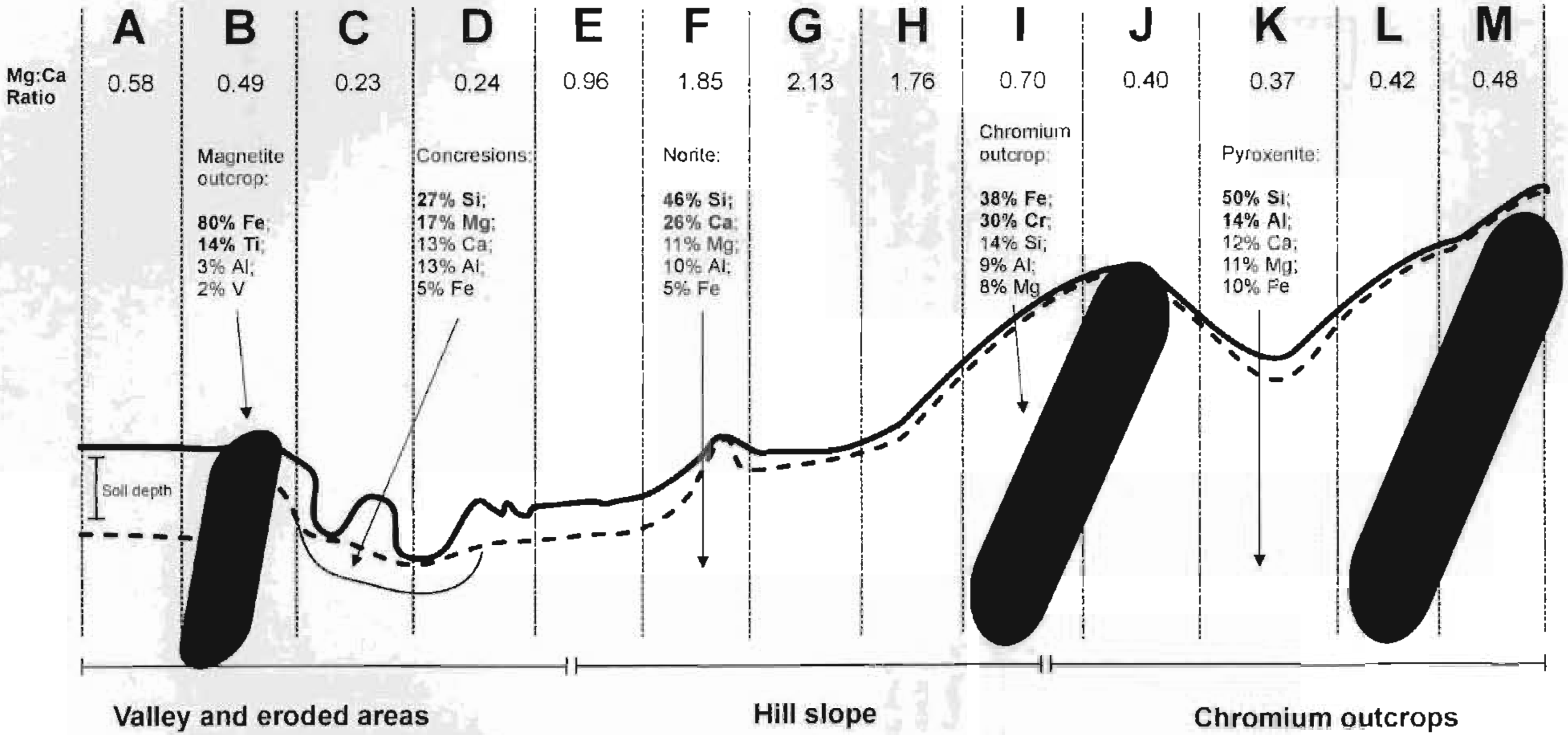
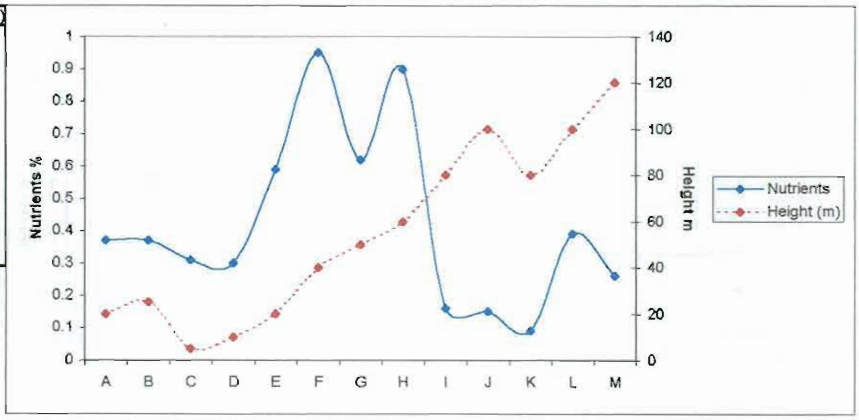
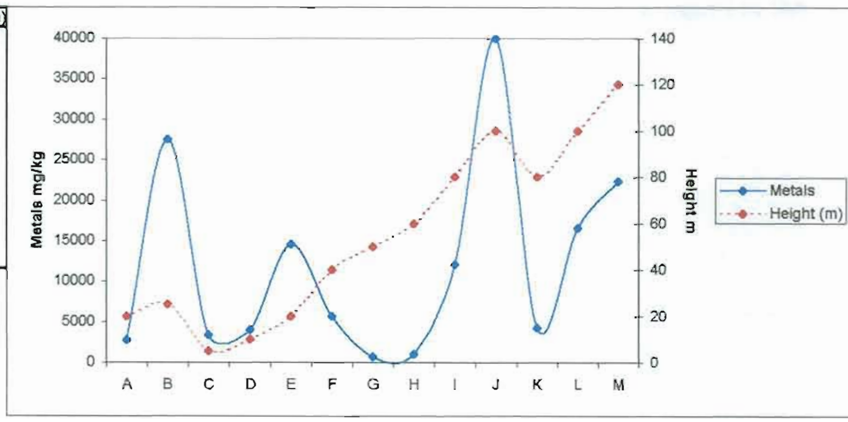


Figure 24 Transect of a catena in the Sekhukhuneland Centre of Plant Endemism with associated underlying rock.

	Nutrients	Height (m)
A	0.37	20
B	0.37	25
C	0.31	5
D	0.3	10
E	0.59	20
F	0.95	40
G	0.62	50
H	0.9	60
I	0.16	80
J	0.15	100
K	0.09	80
L	0.39	100
M	0.26	120



	Metals	Height (m)
A	2794	20
B	27521	25
C	3383	5
D	3994	10
E	14578	20
F	5650	40
G	727	50
H	1050	60
I	12066	80
J	40000	100
K	4287	80
L	16569	100
M	22339	120



	Mg:Ca	Height (m)
A	0.58	20
B	0.49	25
C	0.23	5
D	0.24	10
E	0.96	20
F	1.85	40
G	2.14	50
H	1.73	60
I	0.7	80
J	0.4	100
K	0.37	80
L	0.42	100
M	0.48	120

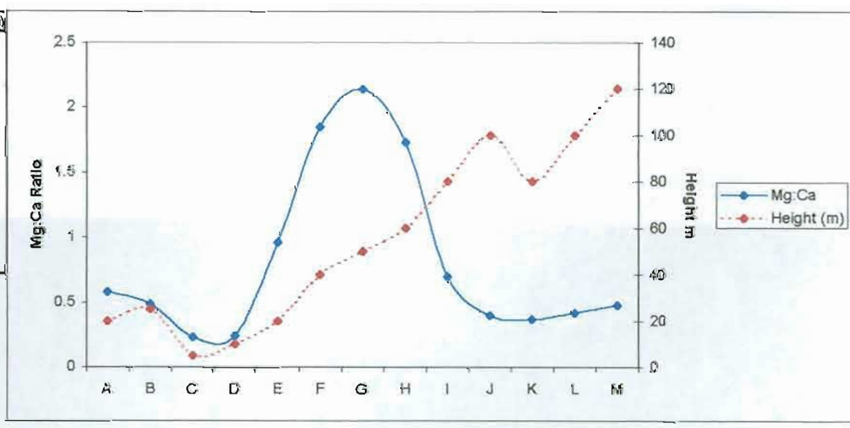
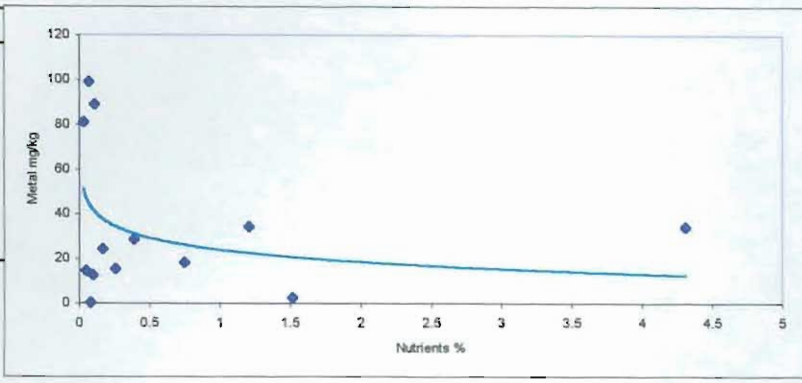
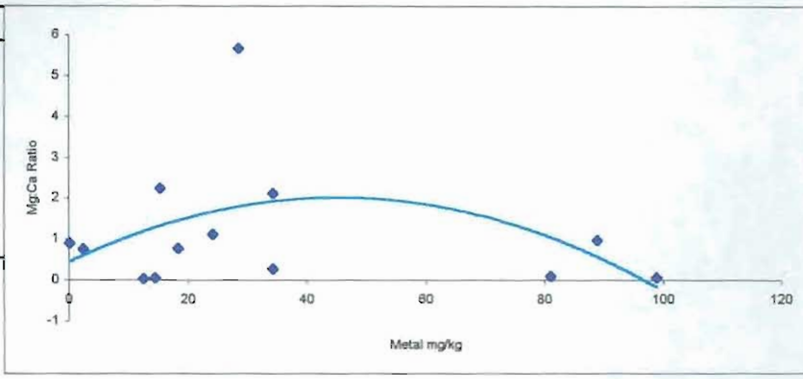


Figure 25 Topographic based distribution of the nutrient levels, heavy metal concentrations and Mg:Ca ratios along the catena (stippling; see Figure 24 for an explanation of A to M). These graphs summarise the results obtained from the soil analysis.

Nutrients %	Metals mg/kg
0.1	12.6
0.05	14.53
0.07	99.01
0.03	81.12
4.31	34.4
1.52	2.45
0.75	18.45
0.08	0.22
0.11	88.95
0.17	24.23
1.21	34.4
0.26	15.43
0.39	28.68



Metals mg/kg	Mg:Ca Ratio
12.6	0.03
14.53	0.05
99.01	0.07
81.12	0.1
34.4	0.27
2.45	0.75
18.45	0.77
0.22	0.89
88.95	0.97
24.23	1.11
34.4	2.11
15.43	2.24
28.68	5.67



Mg:Ca Ratio	Nutrients %
0.03	0.1
0.05	0.05
0.07	0.07
0.1	0.03
0.27	2
0.75	1.52
0.77	0.75
0.89	0.08
0.97	0.11
1.11	0.17
2.11	1.21
2.24	0.26
5.67	0.39

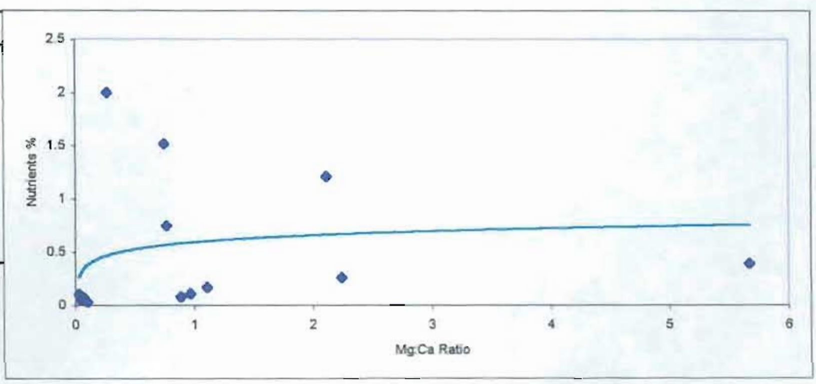
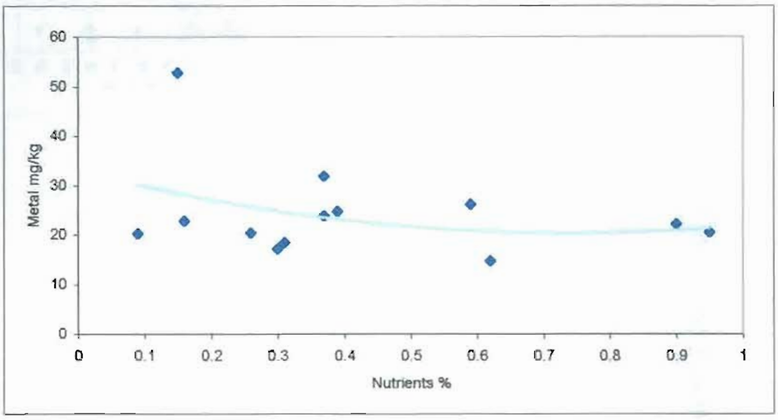
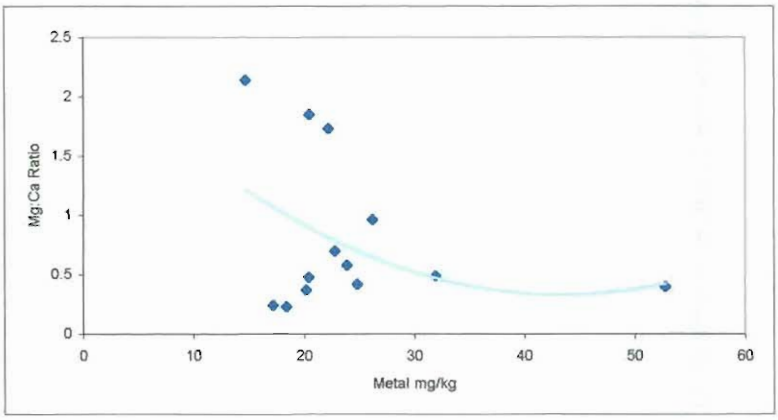


Figure 26 Ordination of selected chemical attributes of the rocks sampled in the Sekhukhuneland Centre of Plant Endemism.

Nutrients %	Metals mg/kg
0.37	23.9
0.37	31.9
0.31	18.4
0.3	17.2
0.59	26.2
0.95	20.5
0.62	14.7
0.9	22.2
0.16	22.8
0.15	52.8
0.09	20.2
0.39	24.8
0.26	20.4



Metals mg/kg	Mg:Ca Ratio
23.9	0.58
31.9	0.49
18.4	0.23
17.2	0.24
26.2	0.96
20.5	1.85
14.7	2.14
22.2	1.73
22.8	0.7
52.8	0.4
20.2	0.37
24.8	0.42
20.4	0.48



Mg:Ca Ratio	Nutrients %
0.58	0.37
0.49	0.37
0.23	0.31
0.24	0.3
0.96	0.59
1.85	0.95
2.14	0.62
1.73	0.9
0.7	0.16
0.4	0.15
0.37	0.09
0.42	0.39
0.48	0.26

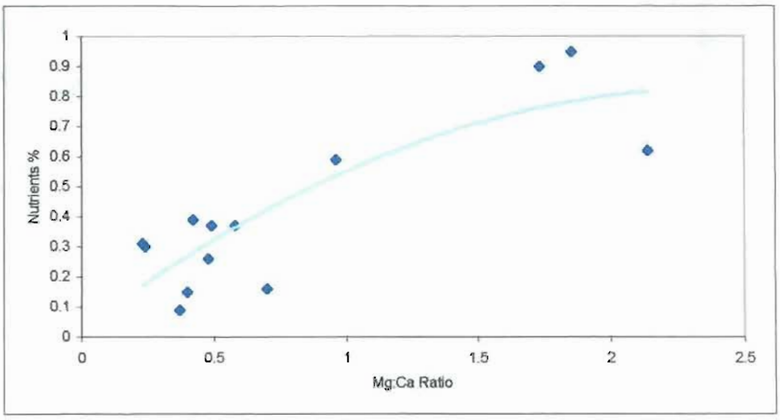


Figure 27 Ordination of selected chemical attributes of the soils sampled along the catena in the study area.

		Nutrient levels	Metal levels	Metal levels	Mg:Ca ratio	Mg:Ca ratio	Nutrient levels
Es	L	5.616	187.1	187.1	15.29	15.29	5.616
Es	R	5.82	946.7	946.7	35.4	35.4	5.82
Ps	L	2.302	9388.8	9388.8	13.43	13.43	2.302
Ps	S	4.792	7642.5	7642.5	54.2	54.2	4.792
Ps	R	3.313	1520.05	1520.05	34	34	3.313
Rk	L	2.813	254.79	254.79	14.76	14.76	2.813
Rk	R	2.228	1382.46	1382.46	27.6	27.6	2.228
Ja	L	3.823	2717.52	2717.52	16.7	16.7	3.823
Ja	R	1.666	2251.28	2251.28	14.34	14.34	1.666
Dg	L	3.203	5611.9	5611.9	15.44	15.44	3.203
Dg	R	1.41	2462.9	2462.9	11.04	11.04	1.41
Pn	L	3.954	248.08	248.08	16.22	16.22	3.954
Pn	R	1.198	614.6	614.6	4.03	4.03	1.198
Bi	L	2.678	328.71	328.71	7.01	7.01	2.678
Bi	R	2.414	989.95	989.95	13.33	13.33	2.414
El	L	4.854	293.59	293.59	60.88	60.88	4.854
El	S	2.897	275.24	275.24	41.32	41.32	2.897
El	R	3.238	2190.57	2190.57	50.24	50.24	3.238
Ib	L	5.453	339.04	339.04	19.64	19.64	5.453
Ib	R	7.027	991.03	991.03	89.3	89.3	7.027
Bs	L	4.761	1398.65	1398.65	86.25	86.25	4.761
Bs	S	1.99	492.18	492.18	23.7	23.7	1.99
Bs	R	4.307	10094.6	10094.6	37.93	37.93	4.307
Rb	L	3.149	383.81	383.81	24.55	24.55	3.149
Rb	S	1.986	226.47	226.47	21.33	21.33	1.986
Rb	R	1.896	1483.93	1483.93	30.23	30.23	1.896
Tr	L	4.257	503.96	503.96	17.1	17.1	4.257
Tr	R	2.072	850.66	850.66	31.23	31.23	2.072
Lc	L	6.563	363.01	363.01	2.6	2.6	6.563
Lc	S	1.112	171.13	171.13	1.75	1.75	1.112
Lc	R	4.11	1152.64	1152.64	12.61	12.61	4.11
Of	L	4.511	388.39	388.39	3.59	3.59	4.511
Of	S	1.484	321.15	321.15	3.02	3.02	1.484
Of	R	2.437	995.31	995.31	5.85	5.85	2.437
Tp	L	5.246	272.02	272.02	10.43	10.43	5.246
Tp	S	10.485	288.55	288.55	80.99	80.99	10.485
Tp	R	6.398	648.19	648.19	22.76	22.76	6.398
Po	L	7.196	146.64	146.64	4.78	4.78	7.196
Po	S	3.734	143.23	143.23	60.76	60.76	3.734
Po	R	7.502	507.67	507.67	13.96	13.96	7.502
Ct	L	3.36	139.88	139.88	4.7	4.7	3.36
Ct	S	3.884	127.95	127.95	23.55	23.55	3.884
Ct	R	4.673	1174.94	1174.94	29.48	29.48	4.673

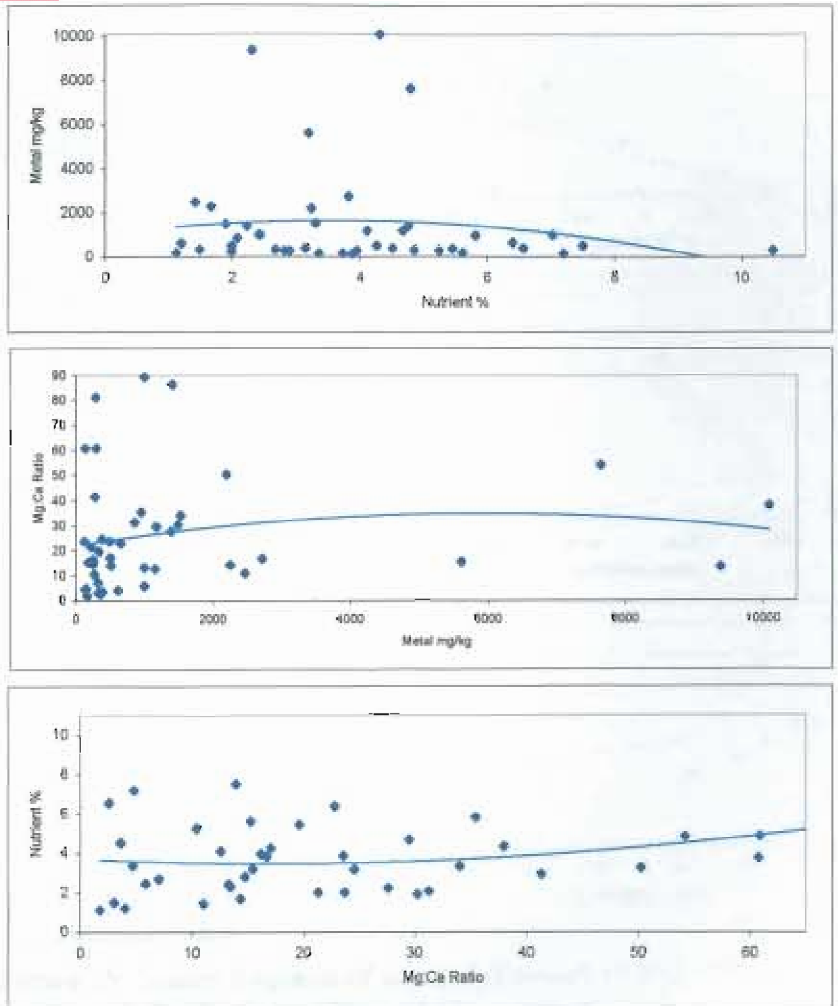


Figure 28 Scatter diagrams of selected chemical attributes of plant material collected along the catena in the study area.

Eroded areas (Figure 29; part I)

		Nutrient %	Metals mg/kg
Bl	L	2.678	328.71
Dg	L	3.203	5611.9
Es	L	5.616	187.1
Ja	L	3.823	2717.52
Pn	L	3.954	248.08
Ps	L	2.302	9388.8
Rk	L	2.813	254.79
Bl	R	2.414	989.95
Dg	R	1.41	2462.9
Es	R	5.82	946.7
Ja	R	1.686	2251.28
Pn	R	1.198	614.6
Ps	R	3.313	1520.06
Rk	R	2.228	1382.46

		Metals mg/kg	Mg:Ca 1:x
Bl	L	328.71	7.01
Dg	L	5611.9	15.44
Es	L	187.1	15.29
Ja	L	2717.52	16.7
Pn	L	248.08	16.22
Ps	L	9388.8	13.43
Rk	L	254.79	14.76
Bl	R	989.95	13.33
Dg	R	2462.9	11.04
Es	R	946.7	35.4
Ja	R	2251.28	14.34
Pn	R	614.6	4.03
Ps	R	1520.05	34
Rk	R	1382.46	27.6

		Mg:Ca 1:x	Nutrient %
Bl	L	7.01	2.678
Dg	L	15.44	3.203
Es	L	15.29	5.616
Ja	L	16.7	3.823
Pn	L	16.22	3.954
Ps	L	13.43	2.302
Rk	L	14.76	2.813
Bl	R	13.33	2.414
Dg	R	11.04	1.41
Es	R	35.4	5.82
Ja	R	14.34	1.686
Pn	R	4.03	1.198
Ps	R	34	3.313
Rk	R	27.6	2.228

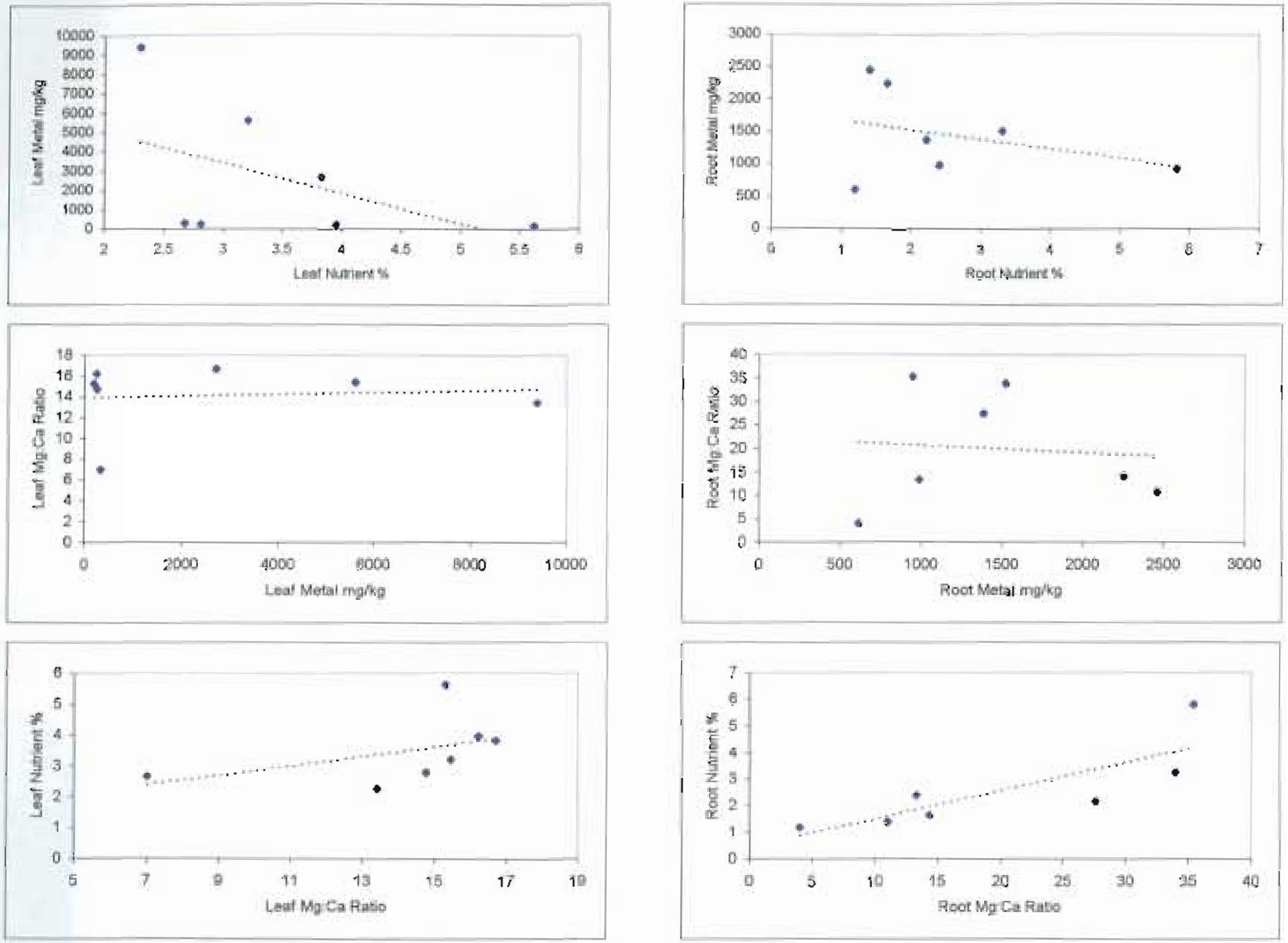


Figure 29 Scatter diagrams of selected chemical attributes of leaf and root material collected along the eroded areas, hill slope and chromitite outcrops of the catena (see Figure 24 for sampling points).

Hill slope (Figure 29; part II)

		Nutrient %	Metals mg/kg
Bs	L	4.761	1398.65
El	L	4.854	293.59
Ib	L	5.453	339.04
Rb	L	3.149	383.81
Tr	L	4.257	503.96
Bs	R	4.307	10094.6
El	R	3.238	2190.57
Ib	R	7.027	991.03
Rb	R	1.896	1483.93
Tr	R	2.072	850.66

		Metals mg/kg	Mg:Ca 1:x
Bs	L	1398.65	86.25
El	L	293.59	60.88
Ib	L	339.04	19.64
Rb	L	383.81	24.55
Tr	L	503.96	17.1
Bs	R	10094.6	37.93
El	R	2190.57	50.24
Ib	R	991.03	89.3
Rb	R	1483.93	30.23
Tr	R	850.66	31.23

		Mg:Ca 1:x	Nutrient %
Bs	L	86.25	4.761
El	L	60.88	4.854
Ib	L	19.64	5.453
Rb	L	24.55	3.149
Tr	L	17.1	4.257
Bs	R	37.93	4.307
El	R	50.24	3.238
Ib	R	89.3	7.027
Rb	R	30.23	1.896
Tr	R	31.23	2.072

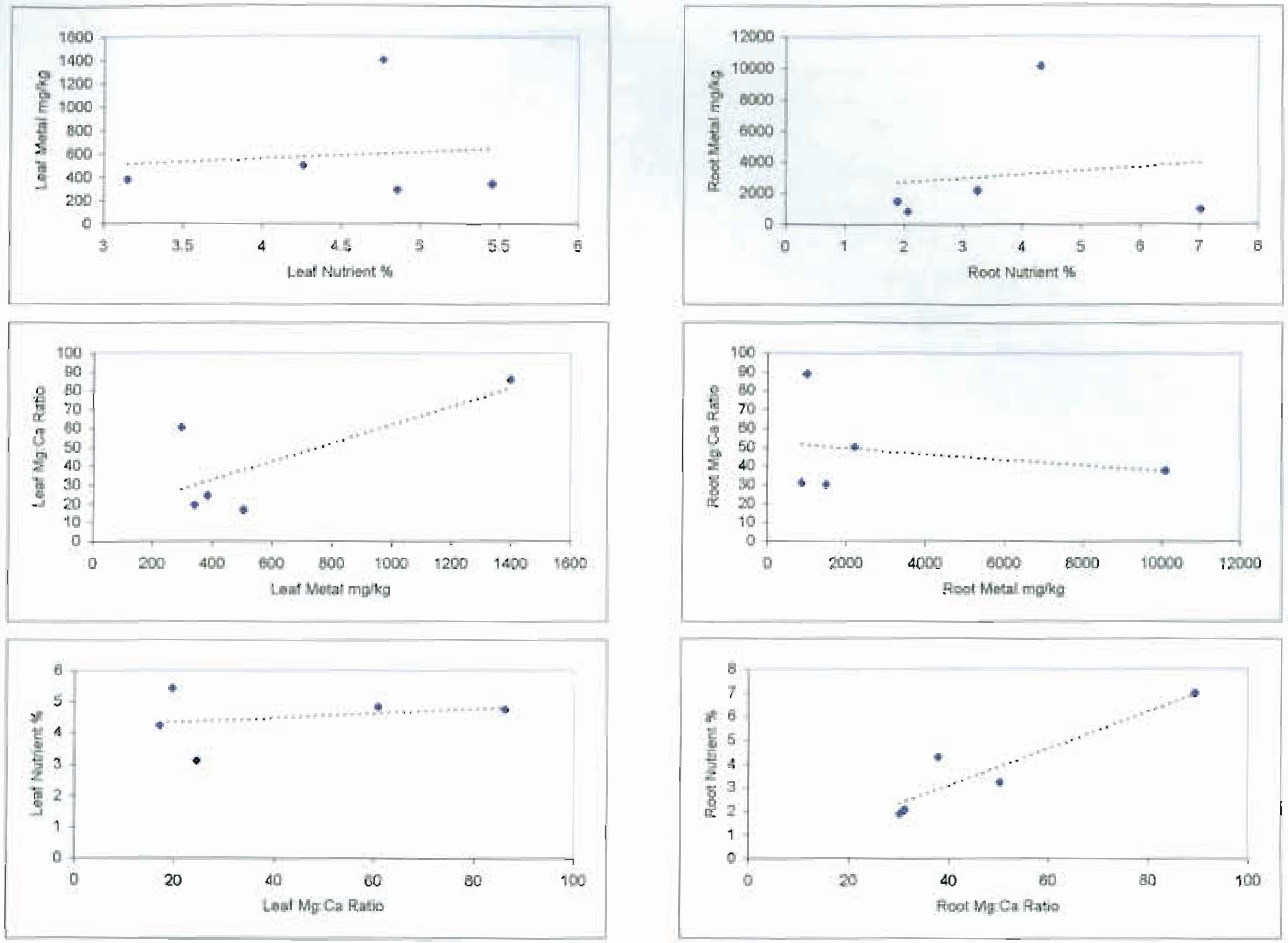


Figure 29 continued. Scatter diagrams of selected chemical attributes of leaf and root material collected along the eroded areas, hill slope and chromitite outcrops of the catena (see Figure 24 for sampling points).

Chromitite outcrops (Figure 29; part III)

		Nutrient %	Metals mg/kg
Ct	L	3.36	139.86
Lc	L	6.563	363.01
Of	L	4.511	388.39
Po	L	7.196	146.64
Tp	L	5.246	272.02
Ct	R	4.673	1174.94
Lc	R	4.11	1152.64
Of	R	2.437	995.31
Po	R	7.502	507.67
Tp	R	6.398	648.19

		Metals mg/kg	Mg:Ca 1:x
Ct	L	139.86	4.7
Lc	L	363.01	2.6
Of	L	388.39	3.59
Po	L	146.64	4.78
Tp	L	272.02	10.43
Ct	R	1174.94	29.48
Lc	R	1152.64	12.61
Of	R	995.31	5.85
Po	R	507.67	13.96
Tp	R	648.19	22.76

		Mg:Ca 1:x	Nutrient %
Ct	L	4.7	3.36
Lc	L	2.6	6.563
Of	L	3.59	4.511
Po	L	4.78	7.196
Tp	L	10.43	5.246
Ct	R	29.48	4.673
Lc	R	12.61	4.11
Of	R	5.85	2.437
Po	R	13.96	7.502
Tp	R	22.76	6.398

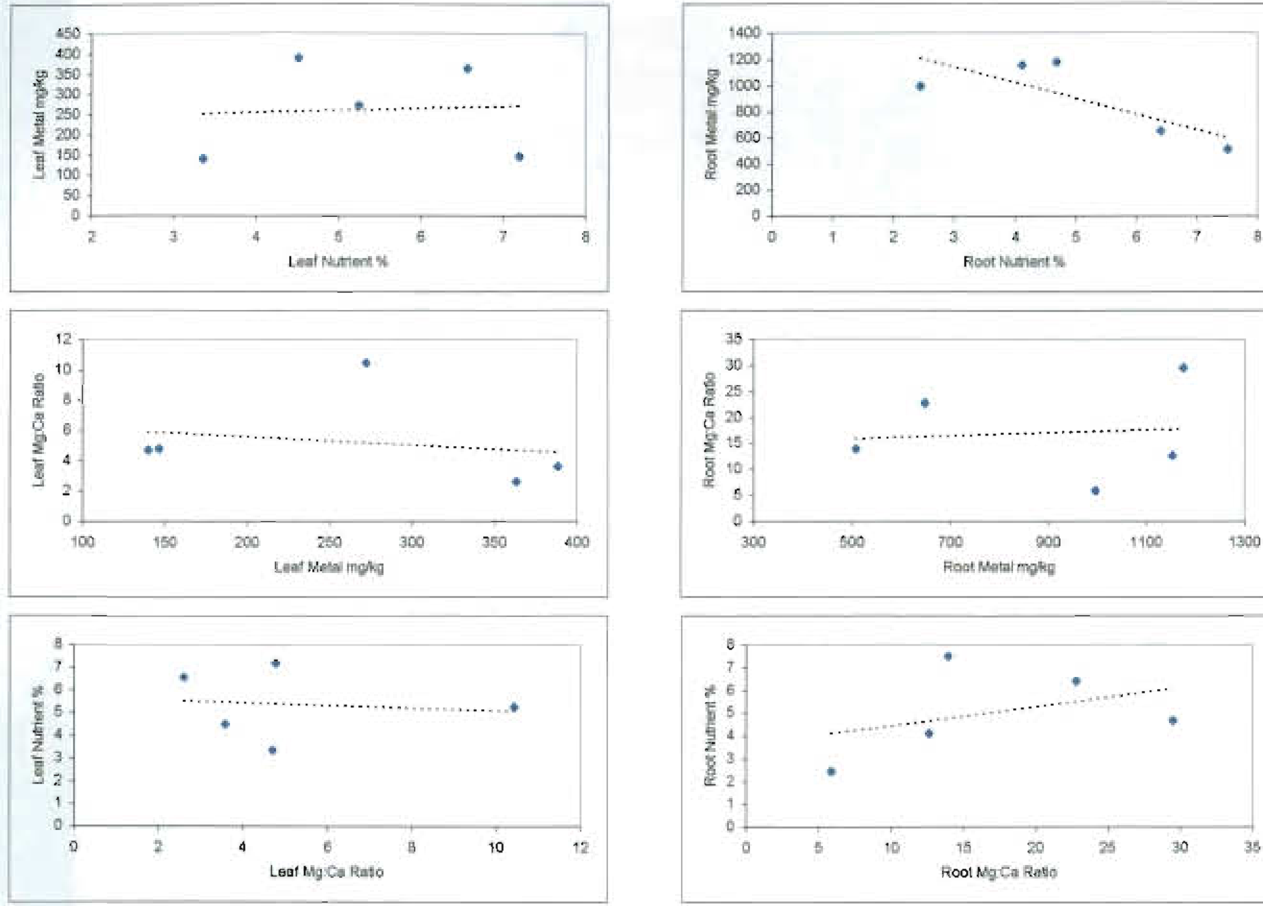


Figure 29 continued. Scatter diagrams of selected chemical attributes of leaf and root material collected along the eroded areas, hill slope and chromitite outcrops of the catena (see Figure 24 for sampling points).

		Soil Nutrients	Plant Nutrients	Soil Metals	Plant Metals	Soil Mg:Ca	Plant Mg:Ca
Es	L	0.37	5.616	23.9	187.1	0.58	15.29
Es	R	0.37	6.82	23.9	946.7	0.58	35.4
Ps	L	0.3	2.302	23.9	9388.6	0.24	13.43
Ps	S	0.3	4.792	23.9	7642.5	0.24	54.2
Ps	R	0.3	3.313	23.9	1520.05	0.24	34
Rk	L	0.37	2.813	18.4	254.79	0.23	14.76
Rk	R	0.37	2.228	18.4	1382.46	0.23	27.6
Ja	L	0.31	3.823	31.9	2717.52	0.49	16.7
Ja	R	0.31	1.666	31.9	2251.28	0.49	14.34
Dg	L	0.3	3.203	23.9	5611.9	0.24	15.44
Dg	R	0.3	1.41	23.9	2492.9	0.24	11.04
Pn	L	0.31	3.954	31.9	248.08	0.49	16.22
Pn	R	0.31	1.196	31.9	614.6	0.49	4.03
Bi	L	0.37	2.678	17.2	328.71	0.58	7.01
Bi	R	0.37	2.414	17.2	989.96	0.58	13.33
El	L	0.59	4.854	20.5	290.59	0.96	60.88
El	S	0.59	2.897	20.5	275.24	0.96	41.32
El	R	0.59	3.238	20.5	2190.57	0.96	50.24
Ib	L	0.95	5.453	26.2	339.04	1.85	19.64
Ib	R	0.95	7.027	26.2	991.03	1.85	89.3
Be	L	0.62	4.761	14.7	1398.65	2.14	86.25
Be	S	0.62	1.99	14.7	492.18	2.14	23.7
Be	R	0.62	4.307	14.7	10094.6	2.14	37.93
Rb	L	0.9	3.149	22.2	383.81	1.73	24.55
Rb	S	0.9	1.986	22.2	226.47	1.73	21.33
Rb	R	0.9	1.896	22.2	1483.93	1.73	30.23
Tr	L	0.16	4.257	22.8	503.96	0.69	17.1
Tr	R	0.16	2.072	22.8	850.66	0.69	31.23
Lc	L	0.15	6.563	42.8	363.01	0.4	2.6
Lc	S	0.15	1.112	42.8	171.13	0.4	1.75
Lc	R	0.15	4.11	42.8	1152.64	0.4	12.61
Of	L	0.09	4.511	20.2	388.39	0.48	3.69
Of	S	0.09	1.484	20.2	321.15	0.48	3.02
Of	R	0.09	2.437	20.2	995.31	0.48	5.85
Tp	L	0.39	5.246	24.8	272.02	0.37	10.43
Tp	S	0.39	10.485	24.8	288.55	0.37	80.99
Tp	R	0.39	6.396	24.8	648.19	0.37	22.76
Po	L	0.26	7.196	20.4	146.64	0.48	4.78
Po	S	0.26	3.734	20.4	143.23	0.48	6.76
Po	R	0.26	7.502	20.4	507.67	0.48	13.96
Ct	L	0.15	3.36	42.8	139.86	0.42	4.7
Ct	S	0.15	3.884	42.8	127.96	0.42	23.55
Ct	R	0.15	4.673	42.8	1174.94	0.42	29.48

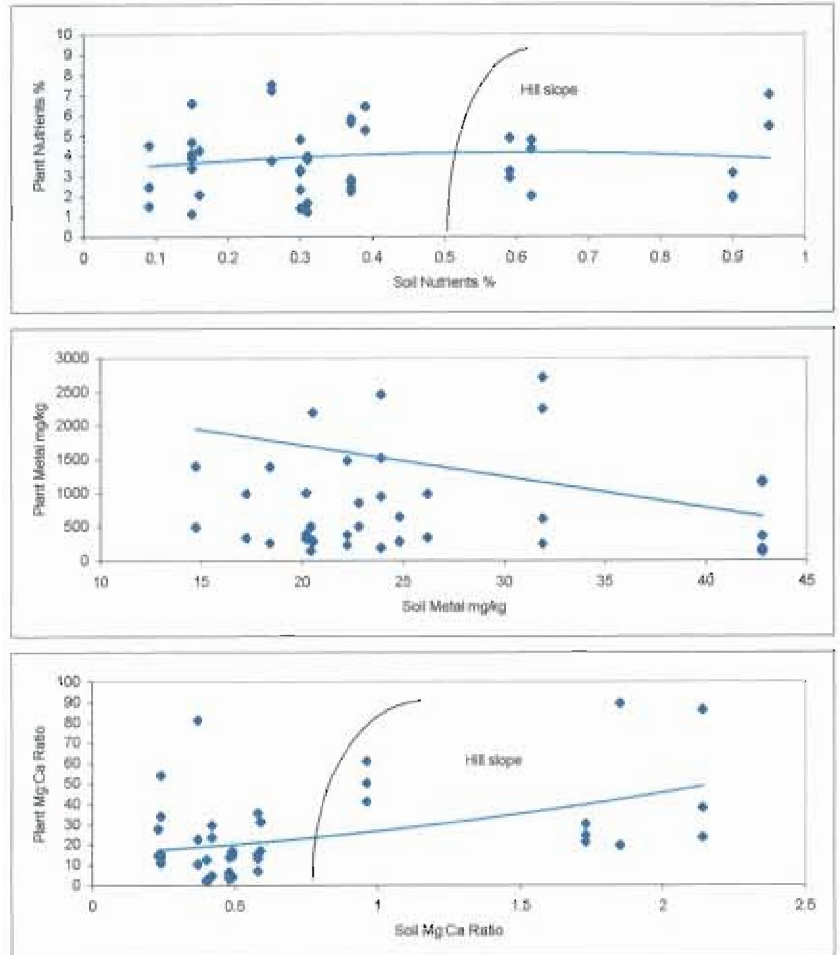
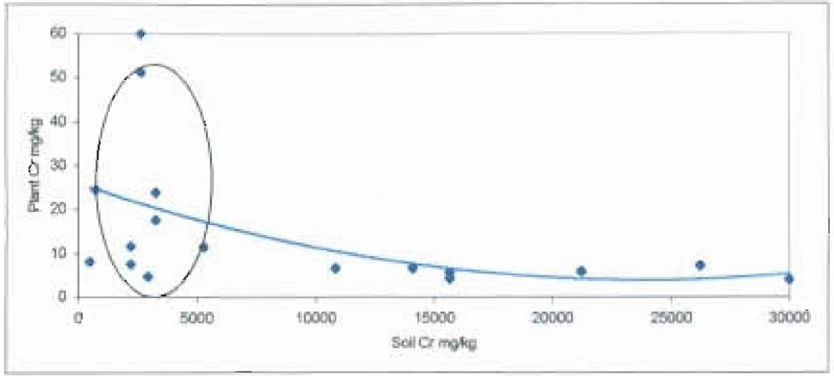


Figure 30 Scatter diagrams depicting the trends of selected chemical attributes in plant-soil associations.

Species (n=5)	Cr mg/kg Plant	Cr mg/kg Soil	Position	Ni mg/kg Plant	Ni mg/kg Soil
Es	17.6	3272	D	16.1	506
Ps	60	2641	C	30	529
Rk	7.5	2214	A	4.3	321
Ja	23.9	3272	D	21.3	506
Dg	51.2	2641	C	24.5	529
Pn	7.1	26238	B	5.4	401
Bl	11.6	2214	A	16.4	321
El	6.6	14102	E	10	201
Ib	6.6	10824	I	12	1028
Bs	11.4	5283	F	7	122
Rb	8	479	G	4.9	81
Tr	24.5	724	H	12.9	114
Lc	4.7	2937	K	2.3	1133
Of	5.5	15671	L	2.1	646
Tp	5.9	21206	M	3.9	812
Po	4.3	15671	L	6.9	646
Ct	3.9	30000	J	3	930



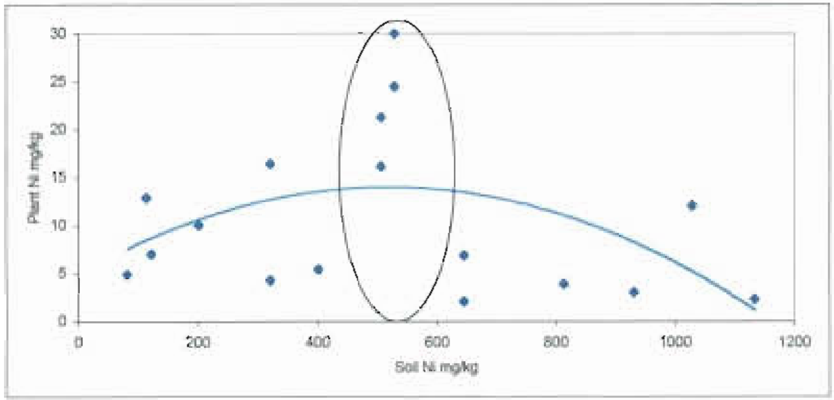


Figure 31 Scatter diagram depicting the optimum accumulation levels of nickel and chromium by plants along the catena.

Table 29 Concentrations of selected elements in the chromitite outcrop soil mixture.

Element	mg/kg (n=25)	Mineral	% (n=25)
Cr	45732	SiO_2	36.48
Ni	910	MgO	17.26
S	392	Fe_2O_3	13.75
V	340	Al_2O_3	8.42
Cl	143	CaO	7.76
Sr	137	Cr_2O_3	7.31
Zn	117	Na_2O	0.88
Co	107	TiO_2	0.23
Zr	33	NiO	0.21
Cu	25	MnO	0.20
Ga	22	K_2O	0.15
W	20	V_2O_5	0.07
Sc	14	P_2O_5	0.02
Y	9		
Pb	7	Mg:Ca Ratio	
Rb	7		
As	6	= 17.26 : 7.76	
Mo	4	= 1 : 0.45	
Nb	3	= 2.22 : 1	
Th	2		

Table 30 Growth comparison of seedlings of *Zea mays* (cultivar SNK 2340 Vryburg) grown in neutral quartzite soil and natural chromium-rich soil [n=3].

	Quartzite soil			Chromium-rich soil			%*
Plants/container	2	4	8	2	4	8	
Week 2							
Average leaf length (mm)	286	304	270	283 (99%)	300 (99%)	254 (94%)	97
Average root length (mm)	238	271	256	220 (92%)	245 (90%)	208 (81%)	88
Average leaf dry mass (mg)	174	189	158	160 (92%)	188 (99%)	152 (96%)	96
Average root dry mass (mg)	79	137	98	77 (97%)	91 (66%)	69 (70%)	78
Week 3							
Average leaf length (mm)	457	426	388	405 (89%)	390 (92%)	339 (87%)	89
Average root length (mm)	314	280	261	303 (96%)	268 (96%)	243 (93%)	95
Average leaf dry mass (mg)	629	452	362	615 (98%)	429 (95%)	319 (88%)	94
Average root dry mass (mg)	459	366	273	407 (89%)	257 (70%)	241 (88%)	82
Week 4							
Average leaf length (mm)	608	527	472	466 (77%)	415 (79%)	352 (75%)	77
Average root length (mm)	361	294	274	319 (88%)	292 (99%)	268 (98%)	95
Average leaf dry mass (mg)	1033	698	598	932 (90%)	560 (80%)	363 (61%)	77
Average root dry mass (mg)	598	413	342	513 (86%)	359 (87%)	313 (92%)	88

**Average biomass production of maize seedlings grown in toxic soils as a percentage of the average biomass production of maize seedlings grown in the control soils.*

Table 31 Concentrations of selected minerals and metals in the roots (R) and leaves (L) of *Zea mays* (cultivar SNK 2340 Vryburg) grown in chromium-rich soil; pH (H_2O) 6.5–7 [n=5]. Shaded areas indicate the highest concentrations for each element during each week.

Plants/container	N%	P%	S%	Mg%	Ca%	Mg: Ca	Cr mg/kg	Ni mg/kg
Week 2								
2 L[1]	4.43	0.688	0.260	0.42	0.77	1.83	4.21	0.52
4 L	3.90	0.046	0.085	0.43	0.59	1.37	4.23	0.34
8 L	3.54	0.577	0.144	0.36	0.56	1.56	4.55	0.15
2 R[2]	2.62	0.230	0.077	0.45	0.47	1.04	32.8	94.8
4 R	2.21	0.467	0.167	0.55	0.54	0.98	23.3	67.9
8 R	1.92	0.592	0.050	0.57	0.62	1.09	22.1	64.9
Average for leaves	**3.96**	**0.436**	**0.163**	**0.40**	**0.64**	**1.59**	**4.33**	**0.34**
Average for roots	**2.25**	**0.419**	**0.098**	**0.52**	**0.54**	**1.04**	**26.1**	**75.9**
Week 3								
2 L	1.51	0.179	0.044	0.41	0.50	1.22	4.05	0.91
4 L	1.58	0.218	0.033	0.40	0.52	1.30	4.07	0.68
8 L	1.63	0.263	0.031	0.47	0.72	1.53	4.75	0.05
2 R	1.12	0.144	0.029	0.68	0.94	1.38	37.9	77.0
4 R	1.37	0.192	0.108	0.46	0.60	1.30	28.4	54.3
8 R	1.23	0.225	0.039	0.39	0.66	1.69	22.0	36.6
Average for leaves	**1.57**	**0.220**	**0.036**	**0.43**	**0.58**	**1.35**	**4.29**	**0.55**
Average for roots	**1.24**	**0.187**	**0.059**	**0.51**	**0.73**	**1.46**	**29.4**	**55.9**
Week 4								
2 L	1.02	0.153	0.021	0.39	0.55	1.41	5.96	1.67
4 L	1.05	0.178	0.020	0.41	0.50	1.22	5.35	0.98
8 L	1.23	0.276	0.021	0.41	0.58	1.41	3.14	1.3
2 R	0.88	0.125	0.038	0.50	0.75	1.50	28.1	42.0
4 R	0.86	0.136	0.050	0.44	0.59	1.34	22.8	53.3
8 R	0.84	0.132	0.039	0.67	1.02	1.52	32.0	64.8
Average for leaves	**1.10**	**0.202**	**0.021**	**0.40**	**0.54**	**1.82**	**4.82**	**1.31**
Average for roots	**0.86**	**0.131**	**0.042**	**0.54**	**0.78**	**1.45**	**27.6**	**53.4**

[1]L = leaves; [2]R = roots

Table 32 Concentrations of selected minerals and metals in the roots (R) and leafs (L) of selected indigenous grass species that grow naturally in the ultramafic soil that was used for the maize experiment. Shaded areas indicate hyperaccumulation of heavy metals.

Species Name	Plant Part	N%	P%	S%	Ca%	Mg%	Cr mg/kg	Ni mg/kg	Fe mg/kg	Mn mg/kg	Al mg/kg	V mg/kg
Stipagrostis	L[1]	0.649	0.053	0.022	0.271	0.074	5.22	10.5	411	22	490	2.2
hirtigluma	R[2]	0.746	0.061	0.014	1.37	0.512	19.5	22	454	23.31	325	4
Heteropogon	L	0.536	0.04	0.025	0.418	0.126	20.3	47.5	811	38.5	1015	5.34
contortus	R	0.822	0.046	0.016	0.365	0.135	32	18.1	924	42.7	437	6.85
Diheteropogon	L	0.361	0.032	0.027	0.656	0.286	13.1	20.9	1687	73.4	3246	3.41
amplectens	R	0.299	0.025	0.027	0.48	0.182	10.1	18.3	1703	39	2926	3.68
Average for leaves		**0.515**	**0.042**	**0.074**	**0.448**	**0.162**	**12.87**	**26.3**	970	**44.63**	**1583**	**3.65**
Average for roots		**0.623**	**0.044**	**0.057**	**0.738**	**0.276**	**20.53**	**19.47**	**1027**	**35**	**1229**	**4.84**

[1]L = leaves; [2]R = roots

Table 33 Diagnostic elements for each major position along the catena.

Element	Valley	Outcrop	Slope
Cu	H[1]	M	M
Mn	H	M	L
S	H	M	L
Cl	H	L	M
Si	H	L	M
Sc	H	L	M
Ti	H	L	M
Ni	M[2]	H	M
Zn	M	H	M
Cr	M	H	L
As	L[3]	H	M
Mo	L	H	M
Ga	L	H	L
Co	H	H	L
Fe	H	H	L
Mg	H	H	L
V	H	H	L
Al	M	M	H
Y	M	M	H
Na	M	M	H
Nb	M	L	H
Rb	M	L	H
Sr	L	M	H
Th	L	M	H
Ca	L	L	H
K	L	L	H
P	L	L	H
Pb	L	L	H
W	L	L	H
Zr	L	L	H

[1]H = high; [2]M = medium; [3]L = low

Table 34 A comparison of the average concentrations of selected elements in the Barberton serpentineferous soils (nine sites) and Sekhukhuneland ultramafic soils (13 samples along one catena). Shaded areas indicate the highest values.

Element	**Minimum**		**Maximum**	
	Barberton*	Sekhukhuneland	Barberton*	Sekhukhuneland
pH	5.84	6.67	7.14	7.84
Mg:Ca ratio	2.11	0.23	10.96	2.14
Mg%	7.06	6.44	29.71	23.44
Ca%	0.57	3.39	12.08	18.53
K%	0.10	0.12	0.47	0.87
Na%	0.02	0.18	0.09	1.88
C%	0.58	0.85	8.78	19.86
N%	0.07	-	0.49	0.77
Cr mg/kg	938	479	3 556	178 020
Ni mg/kg	1 929	81	4 392	1 133

*From Hughes & Noble (1991)

Table 35 A comparison of the average elemental concentrations recorded for soil samples in this study and that of other serpentinite sites in the world. Shaded areas indicate the highest values.

Serpentineferous soil (region)	Soil µg/g (highest figure recorded)		Soil % (average figure recorded)		Soil Ratio	pH (average)	Authority
	Ni mg/kg	Cr mg/kg	Mg %	Ca %	Mg:Ca		
Australia	2 600	4 700	18.6	5.84	3.18	7.25	Forster & Baker (1995)
Canada*	611	-	3.05	3.01	1.01	(4.5)	McHale & Winterhalder (1995)
Cuba	8 954	5 220	9.57	0.48	19.94	-	Reeves *et al.* (1999)
Greece	5 950	-	10.14	1.74	5.83	-	Reeves *et al.* (1995)
New Zealand	1 386	1 843	76.50	8.30	9.22	-	Lee *et al.* (1995)
Philippines	8 100	18 000	6.14	0.57	10.77	6.45	Proctor *et al.* (1995)
South Africa	2 406	5 170	(20.8)	(1)	20.80	6.58	Balkwill *et al.* (1995)
South Africa	4 392	3 556	18.02	7.26	2.50	6.49	Hughes & Noble (1991)
South Africa	3 178	7 329	18.96	1.18	16.07	6.09	Morrey *et al.* (1989)
Zimbabwe	9 375	15 500	10.3	2.20	4.70	6.73	Wild (1974b)
8 countries	**4 695**	**7 665**	**19.21**	**3.15**	**6.1**	**6.6**	**AVERAGE**
Sekhukhuneland	1 133	20 000	17.26	7.76	2.22	7.15	

*Heavy metal contaminated soil

Table 36 A comparison of the average elemental concentrations recorded for plant material in Sekhukhuneland and the Great Dyke of Zimbabwe.

Study Site	Ca%	Mg%	P%	S%
Sekhukhuneland	2.45	0.17	0.33	0.12
Great Dyke*	1.63	1.14	0.11	0.11

Study Site	Cr mg/kg	Ni mg/kg	Fe mg/kg	Mn mg/kg	Al mg/kg	Sr mg/kg
Sekhukhuneland	25	11	735	17	583	82
Great Dyke*	11	792	1066	158	208	41

*From Brooks & Yang (1984)

Table 37 A summary of the nutrient levels, metal concentrations and magnesium:calcium ratios recorded for the sampled plant material.

Species (n=5)	Code*	Plant Part	Nutrient %	Metals mg/kg	Mg:Ca 1:x
Euclea sp. nov.	**Es**	L[1]	5.616	187.1	15.29
Euclea sp. nov.	**Es**	R[3]	5.82	946.7	35.4
Pterothrix spinescens	**Ps**	L	2.302	9388.8	13.43
Pterothrix spinescens	**Ps**	S[2]	4.792	7642.5	54.2
Pterothrix spinescens	**Ps**	R	3.313	1520.05	34
Rhus keetii	**Rk**	L	2.813	254.79	14.76
Rhus keetii	**Rk**	R	2.228	1382.46	27.6
Jamesbrittenia atropurpurea	**Ja**	L	3.823	2717.52	16.7
Jamesbrittenia atropurpurea	**Ja**	R	1.666	2251.28	14.34
Dicoma gerrardii	**Dg**	L	3.203	5611.9	15.44
Dicoma gerrardii	**Dg**	R	1.41	2462.9	11.04
Polygala sp. nov.	**Pn**	L	3.954	248.08	16.22
Polygala sp. nov.	**Pn**	R	1.198	614.6	4.03
Brachylaena ilicifolia	**Bi**	L	2.678	328.71	7.01
Brachylaena ilicifolia	**Bi**	R	2.414	989.95	13.33
Euclea linearis	**El**	L	4.854	293.59	60.88
Euclea linearis	**El**	S	2.897	275.24	41.32
Euclea linearis	**El**	R	3.238	2190.57	50.24
Ipomoea bathycolpos	**Ib**	L	5.453	339.04	19.64
Ipomoea bathycolpos	**Ib**	R	7.027	991.03	89.3
Berkheya insignis	**Bs**	L	4.761	1398.65	86.25
Berkheya insignis	**Bs**	S	1.99	492.18	23.7
Berkheya insignis	**Bs**	R	4.307	10094.6	37.93
Rhus batophylla	**Rb**	L	3.149	383.81	24.55
Rhus batophylla	**Rb**	S	1.986	226.47	21.33
Rhus batophylla	**Rb**	R	1.896	1483.93	30.23
Tinnea rhodesiana	**Tr**	L	4.257	503.96	17.1
Tinnea rhodesiana	**Tr**	R	2.072	850.66	31.23
Leucas capensis	**Lc**	L	6.563	363.01	2.6
Leucas capensis	**Lc**	S	1.112	171.13	1.75
Leucas capensis	**Lc**	R	4.11	1152.64	12.61
Orthosiphon fruticosus	**Of**	L	4.511	388.39	3.59
Orthosiphon fruticosus	**Of**	S	1.484	321.15	3.02
Orthosiphon fruticosus	**Of**	R	2.437	995.31	5.85
Terminalia prunoides	**Tp**	L	5.246	272.02	10.43
Terminalia prunoides	**Tp**	S	10.485	288.55	80.99
Terminalia prunoides	**Tp**	R	6.398	648.19	22.76
Petalidium oblongifolium	**Po**	L	7.196	146.64	4.78
Petalidium oblongifolium	**Po**	S	3.734	143.23	6.76
Petalidium oblongifolium	**Po**	R	7.502	507.67	13.96
Catha transvaalensis	**Ct**	L	3.36	139.86	4.7
Catha transvaalensis	**Ct**	S	3.884	127.95	23.55
Catha transvaalensis	**Ct**	R	4.673	1174.94	29.48

*Abbreviations used for graphs in Appendix 4
[1]L = leaves; [2]S = stems; [3]R = roots