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ORIGINAL ARTICLE

Trace metal uptake by the grass *Melinis repens* from roadside soils and sediments, tropical Australia

C. Pratt · B. G. Lottermoser

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Abstract This study reports on trace metal uptake by the grass species *Melinis repens*, growing in roadside soils and sediments in tropical northeastern Australia. Median total Cu, Pb, Ni and Zn concentrations were significantly ($P < 0.05$) higher in road edge soils (Cu = 61.1 mg/kg, Pb = 97.3 mg/kg, Ni = 28.6 mg/kg, Zn = 729 mg/kg) than in background soils collected away from roads (Cu = 5.8 mg/kg, Pb = 11.2 mg/kg, Ni = 3.7 mg/kg, Zn = 21 mg/kg). Significantly ($P < 0.05$) elevated Zn values were recorded in the stems of the *M. repens* specimens growing on roadside soils (231.6 mg/kg dry weight of tissue) compared with those of grasses growing on background soils (40.8 mg/kg dry weight of tissue). Moreover, median Cu, Ni and Zn values in the roots of roadside grasses (Cu = 29.1 mg/kg, Ni = 2.73 mg/kg, Zn = 169 mg/kg) were significantly ($P < 0.05$) higher than their respective levels in the roots of background *M. repens* samples (Cu = 5.98 mg/kg, Ni = 0.70 mg/kg, Zn = 22 mg/kg). A greenhouse experiment showed that Cu and Zn in road sediments are labile and are available for uptake by *M. repens*. The studied roadside soils and sediments were leached with a diethylenetriaminepentaacetic acid–$CaCl_2$–triethanolamine–HCl extraction solution, which proved to be a rudimentary indicator of Zn availability and uptake to the root tissue of *M. repens*. The results demonstrate that trace metals in roadside grasses have the potential to be directed up the food-chain as grasses are consumed by herbivores. In addition, bioavailable metal contaminants hosted by road sediments have the capacity to impact on ecosystems downstream of roads because these sediments are mobilised by road runoff waters from road surfaces into adjoining catchments.

Keywords Traffic · Metals · Bioavailability · *Melinis repens* · Australia

C. Pratt · B. G. Lottermoser
School of Earth and Environmental Sciences,
James Cook University, P.O. Box 6811,
Cairns, QLD 4870, Australia

Present Address:
C. Pratt (✉)
Institute of Technology and Engineering,
Massey University, Turitea Campus,
Palmerston North, New Zealand
e-mail: C.C.Pratt@massey.ac.nz

Introduction

Roadside soils are sinks for traffic-derived metals (cf. Sutherland et al. 2000), which may be available to plants, animals and fungi dwelling in roadside corridors (cf. Garcia and Millan 1998; Sures et al. 2003). Investigations by Weigmann (1991), Marino et al. (1992) and Viard et al. (2004) found elevated trace metal levels (Cd, Pb, Zn) in earthworms and snails in close proximities to major roads in Europe. Moreover, Ward et al. (1975), David and Williams (1975), Wylie and Bell (1973), Wheeler and Rolfe (1979), Cook et al. (1994), Olajire and Ayodele (1997), Garcia and Millan (1998), Jaradat and Momani (1999), Swaileh et al. (2004) and Viard et al. (2004) have reported elevated Cd, Cu, Pb, Ni and Zn levels in various species of bracken, grass and shrub growing in roadside soils.

Trace metals may be taken-up by plants via contaminated roadside topsoils and airborne particulates (cf. Alloway 1995; Garty et al. 1996; Klumpp et al.

1999; Alaimo et al. 2000). The uptake of traffic-derived metal contaminants by organisms may have negative impacts on the health of roadside ecosystems (Burger et al. 2003; Hund-Rinke and Kordel 2003). For example, the release of polyaromatic hydrocarbons from tyre shreds impacts on the survival rate of aquatic biota (Day et al. 1993; Wik and Dave 2006), and the fish mortality downstream from roads has been related to excessive metal (Cu and Zn) concentrations derived from roads (Forman and Alexander 1998). Moreover, metal contaminants may accumulate up the food-chain in the tissue of animals that feed on these roadside-dwelling organisms (Marino et al. 1992). Forman and Alexander (1998) reported elevated Pb levels in the tissue of mammals living in close proximity to roads.

Much of the previous work on the bioavailability and uptake of trace metals has focused on roadside environments in humid, temperate regions of the northern hemisphere. In contrast, there are no data on the bioavailability of traffic-derived trace metals in roadside soils in wet–dry tropical regions (Turner and Maynard 2003). Additionally, the availability of metals hosted by road sediments in both tropical and temperate regions remains unexplored. Contaminants hosted by road sediments have the potential to impact not only on roadside ecosystems but also on aquatic ecosystems within catchments that receive road runoff waters. Thus, this research aimed: (1) to establish the bioavailable portion of Cd, Cu, Pb, Ni and Zn in roadside soils and road sediments of tropical north-eastern Australia; and (2) to determine the uptake of bioavailable metals in the grass species *Melinis repens* (Red Natal grass).

Study location

Physiography and climate

The study focused on roadside environments adjacent to the Kuranda Range Road, which traverses the Wet Tropics Region of North Queensland, Australia (16°50′S, 145°40′E), approximately 15 km northwest of Cairns (Fig. 1). A field located well away from roads (i.e. representing background) was also sampled as part of the study (Fig. 1).

The study region has a tropical monsoonal climate, with distinct wet and dry seasons and 80% of the annual rainfall falling between November and April. The average annual rainfall in the region is 2,000 mm (Cairns airport weather station, 7 km southeast of the Kuranda Range Road) (Bureau of Meteorology 2006).

Geology, soils and landuse

The Kuranda Range Road passes over large tracts of Hodgkinson Formation, a regionally extensive Devonian succession comprised of turbiditic metasedimentary rocks, and minor late Permian Mt Formatine Granite (Willmott et al. 1988). The lower section of the road overlies unconsolidated Quaternary colluvial, alluvial, coastal dune and estuarine deposits. Soils of the escarpment are red clay loams of metamorphic origin and those of the lowlands are coarse sand and sandy loams formed on Quaternary alluvium (Murtha et al. 1996). The upper section of the Kuranda Range Road is completely forested and is included in the Wet Tropics World Heritage Area. The lowland country

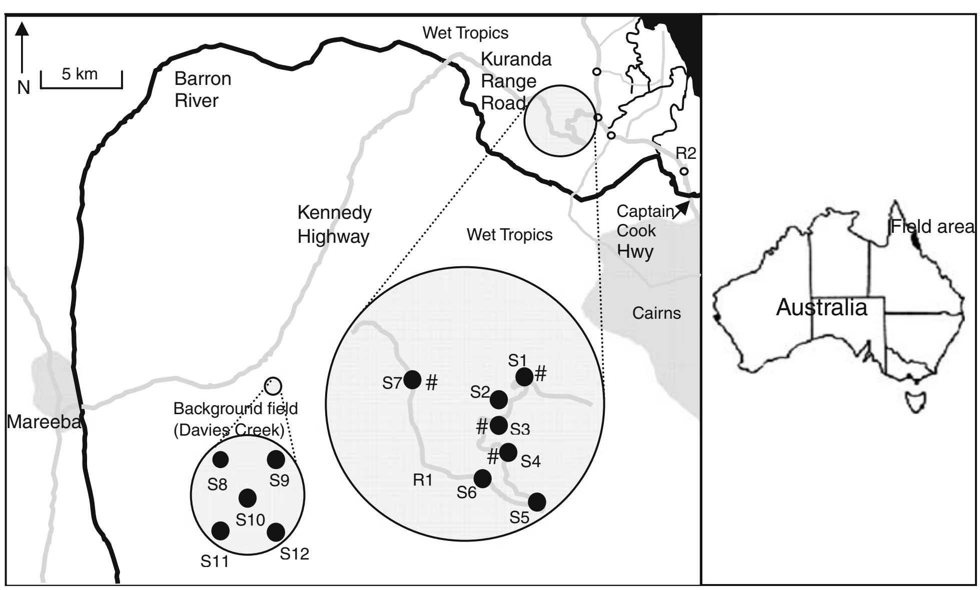

Fig. 1 Regional map of the study area, showing sampling sites for soil, grass (*S*) and road sediment (*R*). At locations marked with *ash symbol*, samples were taken from the road edge as well as 5 m away from the road edge

has been cleared for urban development and sugarcane production.

Vegetation adjacent to the roads

The immediate edge environment adjacent to the Kuranda Range Road hosts significant weed populations. Grass species, including Guinea grass (*Panicum maximum*), dominate the road edge on the upper section of the Kuranda Range Road where canopy cover is dense and light penetration is minimal. However, along the lower and more open section of the Kuranda Range Road, and next to the Captain Cook Highway, grass species including Red Natal grass (*M. repens*) and Rhodes grass (*Chloris gayana*) dominate the road edge environment. *M. repens* is a perennial tussock grass native to South Africa and commonly occurs on road and rail verges and elsewhere in Australia.

Road properties

The Kuranda Range Road accommodates an average daily traffic (ADT) volume of 6,126 vehicles on two single lanes (Cherry, personal communication). The course of the Kuranda Range Road between the coastal plain and the escarpment is convolute, includes 20 sharp bends and has an average grade of 6% (Cherry, personal communication). The road surface comprises basalt aggregate and bitumen, and runoff waters enter local catchments via concrete gutters, swales and overland flows.

Materials and methods

Field sampling and sample processing

Two individuals of *M. repens* were collected from adjacent to the Kuranda Range Road and from the Davies Creek area west of Cairns, respectively (Fig. 1). The sampled specimens were formally identified by the Queensland Herbarium (Brisbane). Following species identification, additional *M. repens* samples were collected immediately adjacent to the Kuranda Range Road (S1–S7, Fig. 1). Where possible, grass samples were also taken at a distance of greater than 5 m from the road edge, although specimens were only observed at distances of 5 m from the road edge at four locations (Fig. 1).

Background samples of *M. repens* were acquired from an open grass field near the Davies Creek Access Road (S8–S12, Fig. 1). This field is an abandoned paddock, located more than 5 km away from the nearest bitumen road and more than 20 km away from any industrial site.

Stem and flower tissues from each grass sample were separated from the roots. The samples were thoroughly washed with distilled water (ICARDA 2001). Stem and flower, and root samples were then weighed out into 10 mL borosilicate glass test tubes, which were transferred into an ashing oven set at 550°C for 48 h (ICARDA 2001). Following cooling, 2 mL of 32% HCl were poured into each tube which were left in a fumehood for 24 h (ICARDA 2001). Two millilitres of 30% H_2O_2 were subsequently added to each tube which was left uncapped in a fumehood for 4 h in order to oxidise the remaining organically bound metals. The solutions were then poured into 12 mL polyethylene screw-cap test tubes. The solution in each tube was made up to 10 mL with distilled water. Test tubes were centrifuged at 4,000 rpm for 20 min and the clear extracts from each tube were retained.

Soil samples were collected from each grass sample location by shaking the roots of the grass samples. Soil samples were oven-dried at 40°C and sieved to <2 mm to remove coarse debris and to retain grain size fractions that potentially host anthropogenic metal contributions. Pratt and Lottermoser (2006) established that metal contaminants in road sediments and soils are not restricted to the fine-grained fractions (<75 μm), but are also hosted by fragments >250 μm, including tyre rubber shreds and metallic shavings.

Greenhouse trial

A greenhouse experiment was conducted to establish the uptake of trace metals from road sediments by *M. repens*. Road sediments were chosen as the plant's substrate because such sediments are flushed from the road surface during runoff events and may add significant metal loads to roadside topsoils and adjoining catchments. A total of 900 g of composite road sediment was collected from the Kuranda Range Road and Captain Cook Highway (R1 and R2, Fig. 1). These sediment batches were sieved to <2 mm to remove coarse debris and litter and placed into two clean Terracotta pots. *M. repens* seeds were planted to a depth of 0.5 cm in each pot in three rows. Five seeds were planted in each row. Pots were watered daily with distilled water. After a period of 15 weeks, when the grasses had grown approximately 0.5 m above the sediment surface level, two grass specimens were taken from the pot containing sediment from the Kuranda Range Road. Only one specimen successfully grew in the sediment from the Captain Cook Highway, and this grass was extricated from the pot. Stem tissue from each grass sample was separated from the roots. The same procedure for digestion and analysis of these specimens was carried out as specified for the field grass samples.

Partial extractions

Metals were extracted from soil and sediment samples using the diethylenetriaminepentaacetic acid (DTPA)–$CaCl_2$–triethanolamine (TEA)–HCl extraction procedure described by Rayment and Higginson (1992). The DTPA–$CaCl_2$–HCl–TEA bioavailable solution was developed by Lindsay and Novell (1978) to examine the micronutrient fertility of soils. Rayment and Higginson (1992) suggested that the solution may simulate the action of plant roots by extracting cations adsorbed onto solid phases. Recently, the solution has also been used to assess metal bioavailability in contaminated soils (Garcia and Millan 1998).

Two and a half grams of each soil and sediment sample (previously sieved to <2 mm), collected from each location shown in Fig. 1, were weighed out and added to a 12-mL polyethylene test tube. Subsequently, 5 mL of the DTPA bioavailable solution were added to each test tube, which was capped and shaken end-over-end for 2 h. For all extraction solutions, the contents of the bottles were centrifuged at 4,000 rpm for 20 min and the clear supernatants were retained for analysis.

Analytical methods

All digested plant samples as well as the DTPA–$CaCl_2$–TEA–HCl extracts were analysed for Cd, Cu, Pb, Ni and Zn using ICP-MS at the Advanced Analytical Centre (AAC, Townsville). In addition, the soil and road sediment samples were analysed for their total Cd, Cu, Pb, Ni and Zn contents, following digestion in HF–HNO_3–$HClO_4$ and using ICP-MS (Cd, Cu, Pb, Ni) and ICP-AES (Zn) techniques at Australian Laboratory Services (ALS, Brisbane). Deionised water with HF–HNO_3–$HClO_4$ was used as the matrix solutions for laboratory standards.

QA/QC

Accuracy and precision of the laboratory's results were determined by analysis of reference soil material GXR-3. A portion of this material was submitted on six occasions to ALS (Brisbane) for total metal analysis (Cd, Cu, Pb, Ni, Zn) by ICP-MS following digestion in HF–HNO_3–$HClO_4$. Deviations from the listed GXR-3 compilation values were for Cd, Cu, Pb, Ni and Zn generally less than 15%. Detection limits for soil and plant digest and extraction samples are given in Table 1.

Results

Soils

Soils collected from the immediate edge of the Kuranda Range Road, 5 m from the road edge and from the background site were analysed for their total Cd, Cu, Pb, Ni and Zn content (Fig. 2). A samples-paired *t*-test was performed to establish whether the metal values of road edge soils were significantly higher than those of background soils. The test revealed that median Cu, Pb, Ni and Zn values in the roadside soils were significantly higher ($P < 0.05$) than their respective median levels in the background soils.

Diethylenetriaminepentaacetic acid-extractable metal values were determined for the soil samples collected from the project area (Fig. 3). Soils that exhibited high total metal concentrations displayed comparatively high DTPA-extractable metal values (Fig. 3). Median DTPA-extractable concentrations of all trace metals analysed were higher in the road edge samples than the background soils (Fig. 3). However, only median DTPA-extractable values for Cu and Zn

Table 1 Laboratory detection limits for solid and liquid samples analysed in the study

	Solid samples				Plant and soil liquid digests			
	ICP-MS (mg/kg)		ICP-AES (mg/kg)		ICP-MS (mg/L)		ICP-AES (mg/L)	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Cd	0.01	500	1	1,000	0.05	50	0.5	1,000
Cu	0.2	10,000	2	50,000	0.10	10,000	1	50,000
Pb	0.2	10,000	2	50,000	0.05	10,000	0.5	50,000
Ni	0.2	10,000	2	50,000	0.10	10,000	1	50,000
Zn	0.2	500	2	10,000	0.10	500	5	10,000

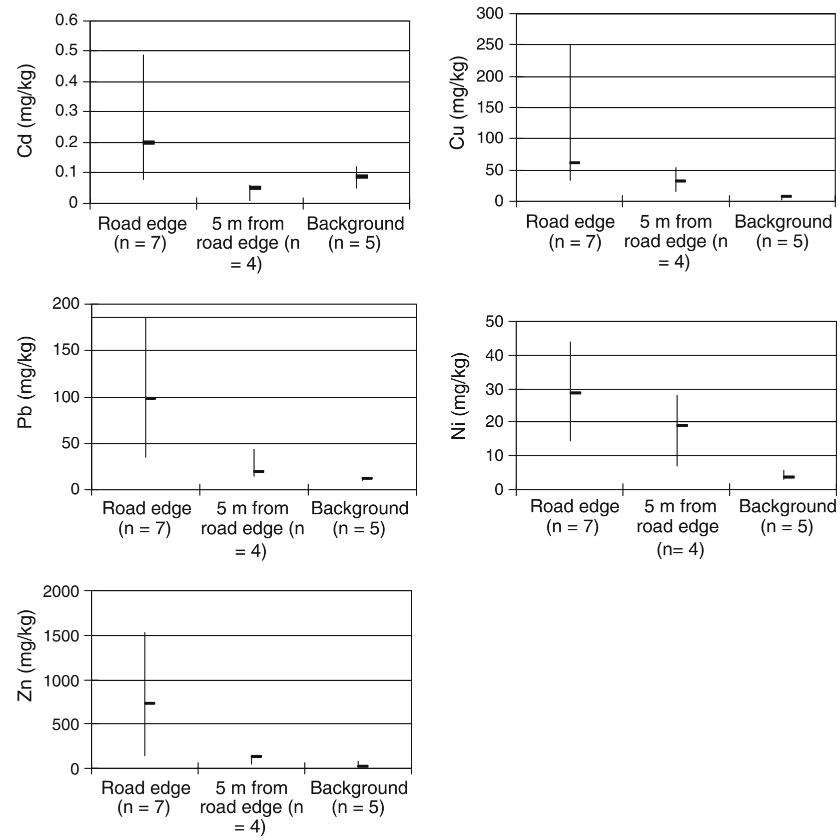

Fig. 2 High-low-close plots of the total metal contents (mg/kg) of soil samples. *Close marks* represent median values. Samples were taken adjacent to the Kuranda Range Road, 5 m from the road edge and from a background site

were significantly ($P < 0.05$) higher in the road edge soils in relation to the background specimens. Individual samples displayed a wide range of DTPA-extractable Cd, Pb and Ni levels, which likely explains why statistically significant differences between road edge and background samples were not observed for the DTPA extracts of these particular metals.

The proportion of each metal extracted by the DTPA solution was calculated relative to its total content in the soil samples (Table 2). The bioavailable proportions of Cu, Ni, Pb and Zn were higher in soils of the road edge than in soils taken 5 m from the road edge (Table 2). By comparison, the background soil samples exhibited the lowest bioavailable Cu, Ni and Zn and the highest bioavailable Pb fraction (Table 2). Bioavailable Cd proportions were highest in the soils 5 m from the road edge (Table 2).

Field grass specimens

Melinis repens specimens were collected from the same locations as the soil samples (i.e. from the immediate edge of the Kuranda Range Road, 5 m from the road edge, and from the background site). The metal chemistry of these grass specimens is shown in Fig. 4. A statistically significant ($P < 0.05$) enrichment in the median Zn value of the roadside stems was observed when compared with that of the background stems. Moreover, for the roots, median Cu, Ni and Zn values were significantly ($P < 0.05$) higher in the road edge samples in relation to the background specimens.

Greenhouse grass specimens

The bioavailability of trace metals in road sediments and their uptake by *M. repens* was assessed using a greenhouse experiment. Metal concentrations in *M. repens* specimens grown in road sediments (Table 3) were similar to those detected in the roadside samples (with the exception of Zn). Zinc values were exceptionally high in the stem tissue of the *M. repens* samples grown in the road sediments (1,210 mg/kg for the grasses in the Captain Cook Highway sediments and 899 mg/kg for the specimens plotted in the Kuranda Range Road sediments, Table 3). The stem Zn values in the greenhouse *M. repens* specimens were much higher than the Zn levels in the stem tissue of the roadside *M. repens* specimens (Fig. 4).

Road sediments

Total trace metal values in the road sediments are given in Table 4. Cadmium was present in the lowest concentrations (0.36 and 0.28 mg/kg in the sediments

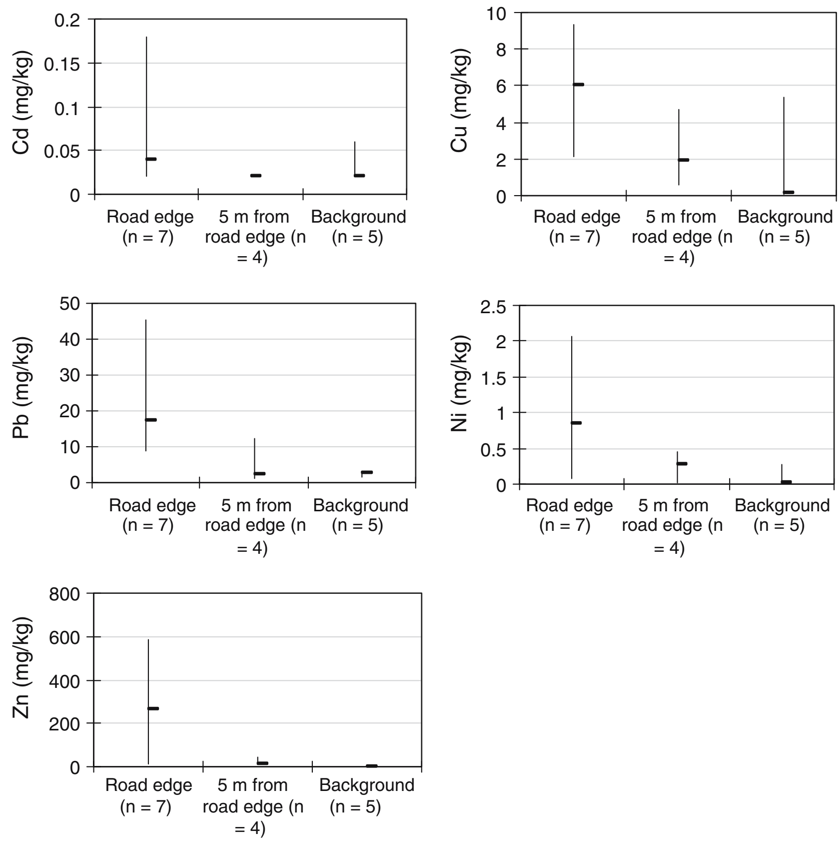

Fig. 3 High-low-close plots of DTPA-extractable metal concentrations (mg/kg) in soils. *Close marks* represent median values. Samples were collected immediately adjacent to the Kuranda Range Road edge, 5 m from the road edge and from a background site

Table 2 Median proportions (%) of DTPA-extractable metals in soils

	Cd	Cu	Pb	Ni	Zn
Road edge (n = 7)	25	9	21	2.2	30
Five meters from road edge (n = 4)	40	6.5	12.5	1.6	10.5
Background site (n = 5)	29	4	24	0.6	6

The results are expressed as percentages of the total individual metal contents

from the Kuranda Range Road and Captain Cook Highway, respectively), whereas Zn exhibited the highest levels (1,330 and 709 mg/kg in the sediments from the Kuranda Range Road and Captain Cook Highway, respectively).

The bioavailable proportions of the studied metals in the road sediments were established using DTPA extractions (Table 5). In the Kuranda Range Road sediments, Zn displayed the highest and Ni the lowest bioavailable proportions of all analysed metals (Table 5). In contrast, Pb exhibited the highest bioavailable fraction in the Captain Cook Highway sediments (Table 5). Bioavailable proportions of Cd, Ni and Zn were much higher in the roadside soils (Table 2) than in the road sediments (Table 5). By comparison, Cu and Pb bioavailable proportions in the road sediments (Table 5) were similar to those hosted by the road edge soils (Table 2).

Discussion

Trace metals in roadside soils

Soils represent an important repository for trace metals. Soil-hosted metals may become remobilised upon interaction with water or be dispersed into freshwater systems by wind, water or gravity (Trombulak and Frissell 2000). Soils adjacent to the Kuranda Range Road possess elevated trace metal concentrations (Fig. 2). The differences in total Cd, Cu, Pb, Ni and Zn values between the road edge samples and those collected at a distance of approximately 5 m from the road edge are particularly distinct.

A recent study by Pratt and Lottermoser (2006) used Pb isotopic ratios and scanning electron microscopy observations to demonstrate the build-up of anthropogenic metal deposits on the Kuranda Range Road. Consequently, it is likely that motor vehicles and road infrastructure, such as signposts and road paving materials, represent the predominant sources of these

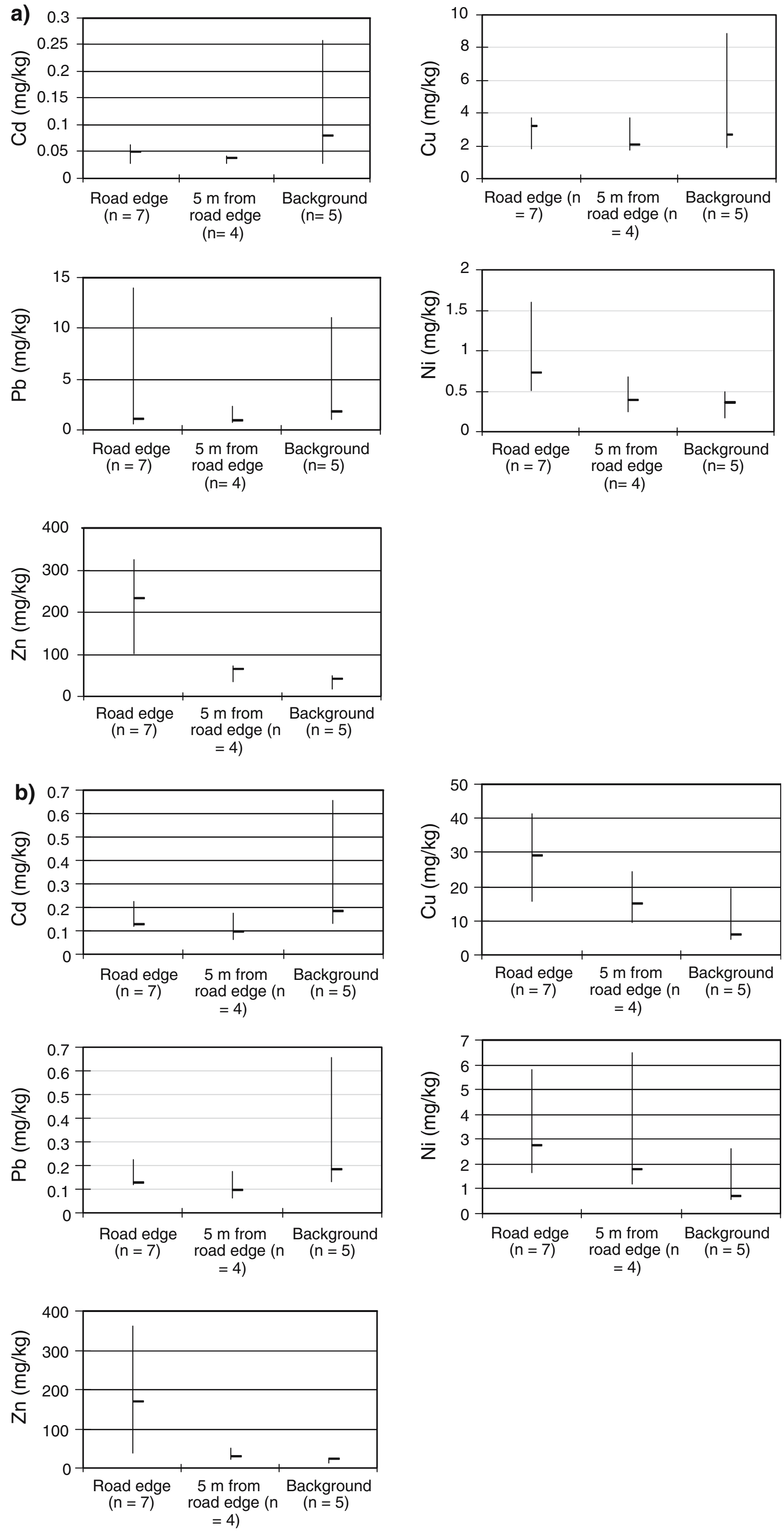

Fig. 4 High-low-close plots of metal contents of: **a** stems; and **b** roots of *M. repens* samples collected from the project area. *Close marks* represent median values. Concentrations in mg/kg are reported relative to the dry weight of each sample

Table 3 Metal concentrations (mg/kg) in *Melinis repens* samples grown in the greenhouse experiment

	Grasses grown in Kuranda Range Road sediments (n = 2)		Grasses grown in Captain Cook Highway roundabout sediments (n = 1)
	Range	Mean	
Stem tissue			
Cd	0.025–0.075	0.05	0.16
Cu	3.9–6.3	5.1	5.2
Pb	2.4–3.4	2.9	0.45
Ni	1.0–1.2	1.1	1.24
Zn	552–1,250	899	1,210
Root tissue			
Cd	0.08–0.18	0.13	0.2
Cu	86–122	104	54
Pb	2.1–2.9	2.5	6.7
Ni	3.3–6.3	4.8	2.1
Zn	105–225	165	254

Concentrations are reported relative to the dry weight of each sample

contaminants in topsoils next to the Kuranda Range Road.

Metal levels in stems of roadside *Melinis repens*

Trace metals, particularly Zn, in roadside soils have been documented to be readily taken-up by the above-ground biomass of roadside plants (cf. David and Williams 1975; Jaradat and Momani 1999). The Zn concentrations in stem tissue of roadside *M. repens* were considerably elevated compared with background samples (Fig. 4). In contrast, the stem tissue of *M. repens* specimens taken next to the road edge exhibited lower Cd, Cu, Pb and Ni values relative to their respective concentrations in the samples acquired from the background site (Fig. 4). Thus, while Zn is taken-up, Cd, Cu, Pb and Ni do not accumulate in the above-ground biomass of *M. repens*, growing immediately adjacent to the road edge. The exclusion of the latter metals in the stem tissue occurs despite the fact that high total Cd, Cu, Pb and Ni levels are present in the roadside substrates.

To date, no studies have investigated trace metal uptake by *M. repens*. Consequently, the findings of this investigation can only be discussed in comparison with other vegetation species examined in the literature. Roadside grass and plant concentration data from this research and other studies are pooled in Table 6.

The median Cd concentration (0.05 mg/kg) in roadside *M. repens* stems is within the reported range of Cd levels (0.01–0.18 mg/kg) in other plant stems from roadside environments (Table 6). In comparison, the median Cu concentration in *M. repens* specimens (3.2 mg/kg) is much lower than those of other vegetation stems (Table 6). Also, Ni levels in the stems of the *M. repens* samples collected from the edge of the Kuranda Range Road are much lower than the Ni values documented in the stems of other roadside plants and grasses (Table 6). This suggests that Cu and Ni in soils next to the Kuranda Range Road are not readily translocated to the stems of *M. repens*.

The roadside *M. repens* stems examined in this research displayed relatively low Pb values compared with Pb concentrations recorded in the above-ground tissue of other roadside plants and grasses (Table 6). Previous studies have demonstrated that Pb concentrations are highly variable in the stem tissue of shrubs and grasses growing next to road edges. For example, Garcia and Millan (1998) reported Pb levels in the

Table 4 Mean total metal concentrations (mg/kg) of road sediments, used in the greenhouse experiment

	Cd		Cu		Pb		Ni		Zn	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Kuranda Range Road sediments (n = 4)	0.36	0.26–0.46	54.4	42–68	66.1	60–80	38.3	35–42	1,330	1,200–1,430
Captain Cook Highway roundabouts sediments (n = 4)	0.28	0.26–0.32	106	65–144	107	92–120	42.8	39–45	709	679–780
Roadside topsoils (n = 7)	0.20		61.1		97.3		28.6		729	

Median metal values of topsoils adjacent to the Kuranda Range Road are shown for comparison

Table 5 Mean proportions (%) of DTPA-extractable metals in road sediment samples

Sediment source	Cd	Cu	Pb	Ni	Zn
Kuranda Range Road (n = 4)	7	4.5	6.5	1.0	9
Captain Cook Highway roundabouts (n = 4)	10.8	9	27	0.6	13

The results are expressed as percentages of the total individual metal contents stems of *Lolium* sp. individuals to be very low; consistently below 10 mg/kg. Soil Pb levels, in which the roadside grasses were growing, were considerably higher, reaching values of 700 mg/kg. In contrast, Ward et al. (1975) determined Pb concentrations of 700 mg/kg in the stem tissue of cottonwood shrub specimens growing next to a remote highway in the North Island of New Zealand. These Pb levels were very high, considering that the ADT on the highway was only 1,200 vehicles and the topsoil Pb levels adjacent to the road were only 160 mg/kg. In general, Pb concentrations in roadside plant tissue are much lower than the respective Pb levels in the topsoil which hosts the plants (Garcia and Millan 1998; Jaradat and Momani 1999). Similarly, this study revealed that Pb values in the *M. repens* stems were much lower than soil Pb values adjacent to the edge of the Kuranda Range Road (Figs. 2, 4).

The Zn concentration recorded in the *M. repens* stems in this study (median value of 231 mg/kg) was much greater than the Zn stem tissue levels of roadside grasses (*Lolium* sp., unspecified), woody shrubs (*Taraxacum* spp., *Anabasis articulata*), small flowering plants (*Inula viscose*) and bracken (*Pteridium esculentum*) recorded in the literature (Table 6). The high Zn concentrations in topsoils adjacent to the Kuranda Range Road have led to high Zn values in the stem tissue of *M. repens* specimens, growing in these soils. It is obvious that Zn is strongly available to roadside vegetation.

Metal levels in roots of roadside *Melinis repens*

Copper and Zn exhibited the highest values in the root tissue of the roadside *M. repens* samples. This result is expected given that of the metals analysed, only Cu and Zn are essential elements for plants (Siegel 2002). The median concentrations of Cu and Zn in the root tissue of the road edge *M. repens* specimens were 29.1 and 169 mg/kg, respectively. These values are elevated above the ‘‘average chemical composition’’ values for plants which are 9 mg/kg for Cu and 70 mg/kg for Zn (Faure 1991), reflecting the likelihood that traffic activities in the study area have led to metal contamination of *M. repens* grass roots.

Cook et al. (1994) examined metal uptake by the stem and root tissue of a woody shrub (*Taraxacum* spp.) adjacent to a highway in Greece. Their results indicate a greater range of Cu and Pb levels in the root tissue of the roadside plants when compared with the stems, with higher levels of these metals generally present in the roots (Table 6). Zinc concentrations, however, were found to be higher in the stem tissue of the shrub specimens (Cook et al. 1994). Thus, the findings of this study are in agreement with those of Cook et al. (1994) despite differences in the vegetation type examined.

The greenhouse trial

The results of the greenhouse trial showed that trace metals hosted by road sediments, particularly Zn and Cu, are readily bioavailable to the roots and stem of *M. repens*. In fact, Zn levels in the stems of the greenhouse *M. repens* samples were approximately 3–5 times higher than respective stem Zn concentrations in the road edge grasses (Table 3). The accumulation of such high Zn values in the greenhouse *M. repens* samples implies that the Zn in the road sediments is present in a highly mobile form.

Chemical reagents as bioavailable markers: strengths and limitations

Correlation analyses were performed on DTPA-extractable and total soil metal contents and the trace metal values of *M. repens* tissue, with both sample types (i.e. root and stem) obtained from the edge of the Kuranda Range Road. Correlation matrices were performed on log-transformed data. The correlation coefficients (R^2 values) between the soil-DTPA and stem tissue metal values as well as the total soil and stem tissue metal concentrations are very poor (<+0.34 and <+0.1, respectively). In fact, none of the correlations are significant at the $P < 0.01$ or 0.05 intervals. Stronger positive relationships between the soil-DTPA and root metal contents as well as the total soil and root metal values were observed, although only in the case of Zn is the correlation significant at the $P < 0.05$ level (+0.96 and +0.97, respectively). Thus, only the soil-DTPA Zn value is a reliable indicator of Zn uptake in *M. repens*.

The DTPA extractions performed in this study permitted quantification of the bioavailable metal proportions in the roadside soils. The results documented in Table 2 showed higher DTPA-extractable proportions of Cu, Ni and Zn in the roadside soils relative to those soils collected 5 m from the road’s edge and from the background site. Therefore, the anthropogenic fraction of these metals in the roadside soils is readily bioavailable, especially Zn.

The results of this study demonstrate some strong limitations in using extraction solutions to infer metal bioavailability in soils and sediments. The analyses shows that DTPA extracts (or in fact, any other chemical extracts) cannot be used to infer the actual uptake of metals in plants. Moreover, the root tissue of

Table 6 Metal concentrations in the stem and root tissue of various roadside plants

Author/plant species	Road studied/traffic density (where given)	Metal concentrations (mg/kg)									
		Cd		Cu		Pb		Ni		Zn	
		P	S	P	S	P	S	P	S	P	S
Stem tissue											
This study/*Melinis repens*	Kuranda Range Road/6,126 ADT	0.05	0.2	3.2	61.1	1.1	97.3	0.7	28.6	232	729
Cook et al. (1994)/ *Taraxacum* spp.	Highway, Thessaloniki, Greece	–	–	57	210	85	620	–	–	130	590
David and Williams (1975)/*Pteridium esculentum* (bracken)	Hume Highway, NSW, Australia	0.04	0.06	4.7	1.5	19.1	12.4	–	–	52	29
Jaradat and Momani (1999)/*Anabasis articulata* (woody shrub)	Highway, Amman, Jordan	–	–	31.3	29.7	7.3	189	–	–	99	122
Ward et al. (1975)/ *Cassinia vauvilliersii* (Cottonwood)	State Highway, New Zealand/1,200 ADT	–	–	–	–	700	160	–	–	–	–
Wylie and Bell (1973)/ *Chloris gayana* (grass)	Cunningham Highway, South East Queensland, Australia/16,000 ADT	–	–	–	–	41 and 64	84 and 207	–	–	–	–
Garcia and Millan (1998)[a]/*Lolium* sp. (grass)	Main Road, Gipuzkoa, Spain/30,700 ADT	0.13	0.84	10.8	162	5.1	471	–	–	27	463
Swaileh et al. (2004)/ *Inula viscose* (small flowering plant)	Nablus-Ramallah Hwy, West Bank/120,000 ADT	0.10	0.27	10.6	60.4	7.3	87.4	4.9	18.9	48	82
Olajire and Ayodele (1997)/grass sp.	Ibadan, Nigeria	0.18	2.7	8.9	80.5	205	730	10.9	115	43.5	213
Wheeler and Rolfe (1979)/*Poa pratensis* (bluegrass)	Highway, Illinois, USA/ 8,100 ADT	–	–	–	–	195	1,220	–	–	–	–
Awofolu (2005)[a]/ common grass	Major roads, Lagos, Nigeria/ 10,000 ADT approximately	0.01–0.07	0.01–0.12	0.1–1.48	0.1–2.90	0.01–0.14	0.02–0.23	–	–	0.19–1.80	0.51–3.35
Root tissue											
This study/*M. repens*	Kuranda Range Road	0.13	0.2	29.1	61.1	7.8	97.3	2.7	28.6	169	729
Cook et al. (1994)/ *Taraxacum* spp.	Highway, Thessaloniki, Greece	–	–	71	210	114	620	–	–	102	590

Median values are presented relative to dry weight for each species

P plant, *S* soil

[a] Denotes that portion of plant analysed has not been specified

M. repens preferentially accumulates trace metals. Bioavailable reagents cannot differentiate this partitioning.

Transfer of traffic-derived metals into ecosystems

This investigation demonstrates that the stem and, particularly, the root tissue of *M. repens* accumulate traffic-derived trace metals. In particular, there is significant enrichment of Cu and Ni in the root tissue and of Zn in both the roots and stems. Road corridors represent ecological niches for plant and animal life and, the biomass of such grass species represents a food source for other animals (cf. Awofolu 2005). Consequently, traffic-derived trace metals present in roadside topsoils and vegetation may be transferred to grazing animals, including insects and earthworms. While the uptake of trace metals from soils into plants is restricted in area to no more than 5 m from the road edge, bioavailable trace metals bound to road sediments could be transferred by road runoff waters to catchments and aquatic organisms distant to road sources.

Conclusions

This study has demonstrated that topsoils adjacent to the Kuranda Range Road possess elevated Cd, Cu, Pb, Ni and Zn values. Significant proportions of the metals (notably Cu, Ni and Zn) are bioavailable to *M. repens* grasses growing on roadside soils. The uptake of metals is mainly restricted to the root tissue of the studied grass species. However, Zn is also concentrated in the stems of *M. repens*. The DTPA–$CaCl_2$–TEA–HCl extraction solution proved to be only a rudimentary indicator of Zn uptake to the studied grass species. Tissue analysis is recommended as the most effective measure of contaminant uptake. Metals in roadside grasses have the potential to be directed up the food-chain because grasses are consumed by herbivores. Moreover, bioavailable contaminants hosted by road sediments have the capacity to impact on ecosystems downstream of roads, as these sediments are mobilised from road surfaces into adjoining catchments by road runoff waters.

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