

DIEBACK IN TROPICAL MONTANE FORESTS OF SRI LANKA: ANTHROPOGENIC OR NATURAL PHENOMENON?

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ABSTRACT

Forest health of Tropical Upper Montane Rain Forests of Sri Lanka which are considered as "Biodiversity Hotspots" merit global attention. They are now rapidly diminishing due to a hitherto little understood phenomenon called forest dieback. This study examines the contribution of possible soil nutrient and toxic element factors for the health of *Hakgala* Tropical Upper Montane Forest. During the first stage, N, K, Ca, Mg, Zn, Cu, Fe, Mn and Al levels were studied in plots situated in the forest at locations of different dieback stages. Al, Mn, Fe and Pb concentrations in 30 individuals of 08 most susceptible plant species at different dieback stages and of soils of the immediate vicinity were determined during the second stage. Collected plant leaves were analyzed for total element levels and soils for extractable element levels.

Geographical locations and the rate at which forests are being affected since last three decades suggest that forest dieback in Sri Lanka is not caused by a natural phenomenon. Results of the first stage of the study reveal that N, K, Ca, Mg, Zn, Cu were not in excess nor at deficiency levels. The second stage revealed the presence of high DTPA extractable Pb, Mn, Fe and KCl extractable Al in soils. The most important observation was the presence of higher than normal accumulations of Pb and Al in plant leaves. The plants belonging to some dieback-susceptible species showed an increasing trend of both Al and Pb levels in their leaves.

Keywords: tropical montane forest, dieback, acidic soils

INTRODUCTION

Dieback of Tropical Upper Montane Rain Forests (UMRF) has become a severe environmental problem in Sri Lanka. This phenomenon has been observed in UMRF of Horton Plains National Park (HPNP) (Perera, 1978, Werner, 1982, Hoffman, 1988), Pidurutalagala ridge, Kobonilgala near Cobet's gap in Knuckles range (Werner, 1988) and at summits of Hakgala Strict Nature Reserve (SNR) (Wijesundara, 1991). Also, two early foresters, De Rosayro (1946) and Chapman (1947) have reported the unhealthy

nature of UMRF in Sri Lanka. Adikaram and Mahaliyanage (1999) found that 38% of the trees in HPNP were either affected or dead. The authors observed that more than 90% of canopy trees on the Thotupolakanda ridge in the Horton Plains, about 75% of the Hakgala peak and a considerable number of trees in Riversturn area of the Knuckles range have already died (Figure 1). This rapid expansion - dying of about 90% of forest at some locations within 3-4 decades - casts doubts about the possibility of a natural phenomenon.

Even though various hypotheses such as acid rain, diseases, bark damage by samburs (*Cerus unicolor*), soil nutrient imbalance and soil toxicity have been put forward, recent studies exclude most of these (Adikaram and Mahaliyanage, 1999, Ranawana, 1999, Ranasinghe and Dissanayake, 2003, Gunawardana, 1988). Ranasinghe *et al.* (2007) recognized a relationship between spatial distribution of forest dieback in the HPNP and excess soil Pb, Al, Mn and Fe levels. Chandrajith *et al.* (2009) have studied the relationship between soil plant major and trace element levels and concluded that there is no direct evidence for the cause of forest dieback in Horton Plains National Park in Sri Lanka. These authors recognize it as a possible natural phenomenon. Also, they have not recorded excess Pb amounts in plants, but recorded higher accumulations of Mg in dead plants and lower levels of Ca in soils in affected areas. However, lack of sufficient studies covering the entire upper montane area of the country hinders any possible conclusions on causes of forest dieback. The present study was carried out in UMRF of the Hakgala SNR in order to comprehend the relationship between soil and plant elemental levels and forest health.

Physiography and Climate

Hakgala UMRF is situated in the Central Highlands of Sri Lanka. It covers a mountain range with three peaks at elevations varying from 1650 m to 2170 m above MSL. (Figure 2). This UMRF covering an area

of 423 ha has been declared a Strict Nature Reserve (SNR). Hakgala mountain range serves as a catchment for Uma Oya, which is a major tributary of Mahaweli, the longest river in Sri Lanka. This area receives rainfall from both northwestern and southwestern monsoons, the rainfall in the southwest monsoon period being markedly higher than that of the northeast monsoon. Mean annual rainfall of the area is 2400 mm (Meijer, 1980, 1981). The mean annual temperature is 15.5°C, without marked seasonal fluctuations. Fog occurs frequently in the area during early afternoons and may persist throughout the day during rainy periods of southwestern monsoon.

Geology and Soil

Hakgala SNR belongs to the Highland Complex of Sri Lanka, which consists mainly of Precambrian high grade metamorphic rocks (Cooray, 1994). Garnet sillimanite biotite graphite gneiss, charnokites and marble underlie the area (Figure 3). This area is situated in the axial region of the Gurutalawa synform (GSMB Maps, 1997).

Red yellow podzolic soil with a dark "A" horizon is the major soil group in the area (Panabokke, 1996). However, the dark "A" horizon was absent in most of the sampling locations situated on slopes.



Figure 1: A dying Upper Montane Rain Forest, Hakgala, Sri Lanka

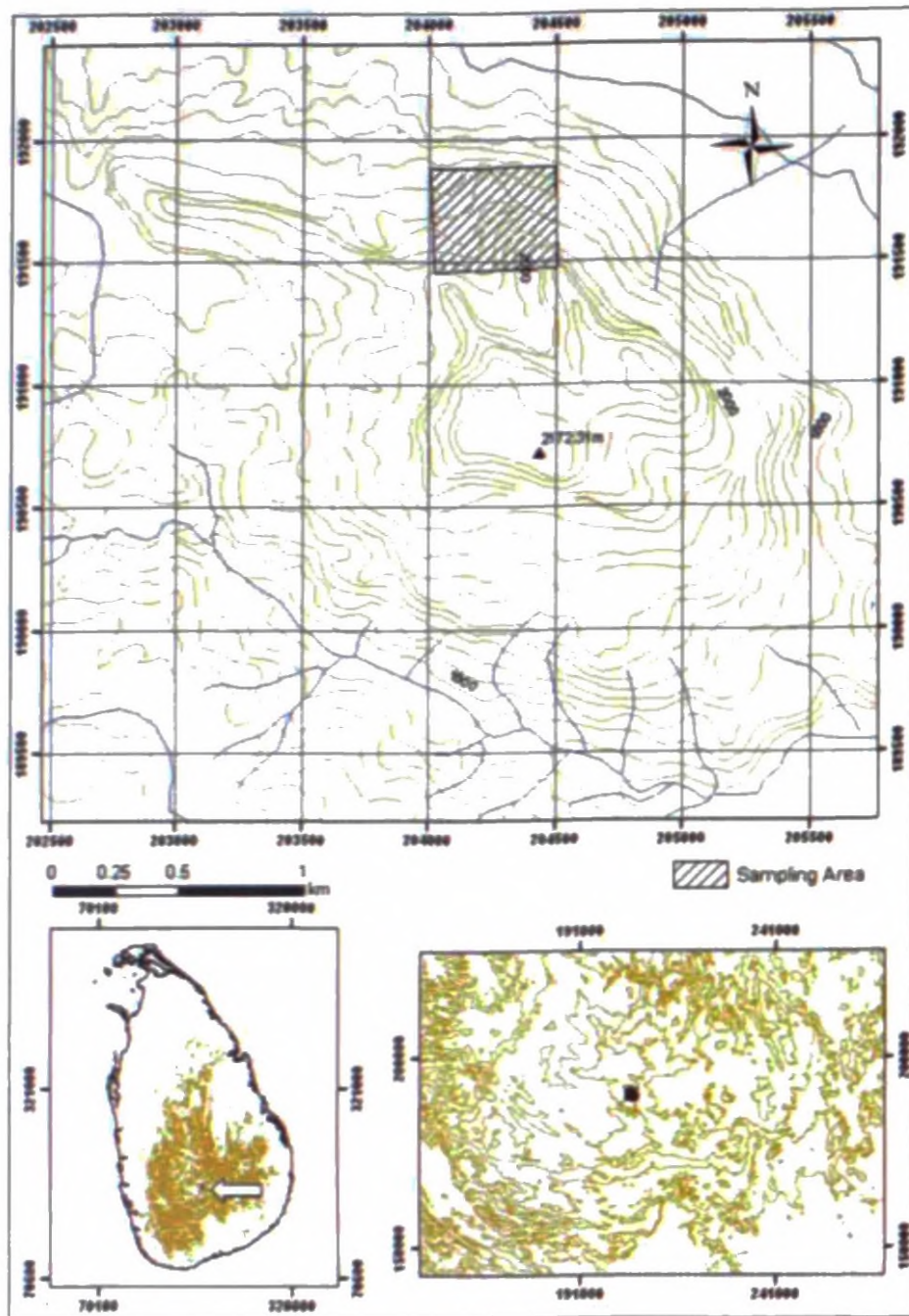


Figure 2: Topography of the study area of Hakgala

Vegetation

Generally, tree heights of the Hakgala SNR forest vary between 6 and 10 m but decrease sharply on wind-exposed ridge tops where dwarf trees of height about 1m are dominant. Pygmy forest with stunted trees is a characteristic feature of the Hakgala SNR. At lower elevations, the forest is extremely dense having thick undergrowth. In these areas, tall trees with heights varying from 15 to 25 m are occasionally observed. Almost all the stems of these trees are covered with crustose, foliose or squawalose lichens. In moist areas where a dense growth of vegetation is observed, fruticose lichens such as *Usnea barbata* are abundant. In addition to this epiphytic form, many bryophytes, ferns and dicotyledons plants are common. Orchids are the only epiphytic monocots found in the Hakgala forest. *Lauraceae*, *Myrtaceae*, *Clusiaceae*, *Symplocaceae* and *Euphorbiaceae* are the dominant families in the upper layers while undergrowth consists of various species of *Strobilanthes*.

A study by Adikaram and Mahaliyanage (1999) showed that *Syzygium rotundifolium*, *Ilex walkeri*, *Symplocos bractealis* and *Syzygium sclerophyllum* were highly susceptible to dieback in the HPNP.

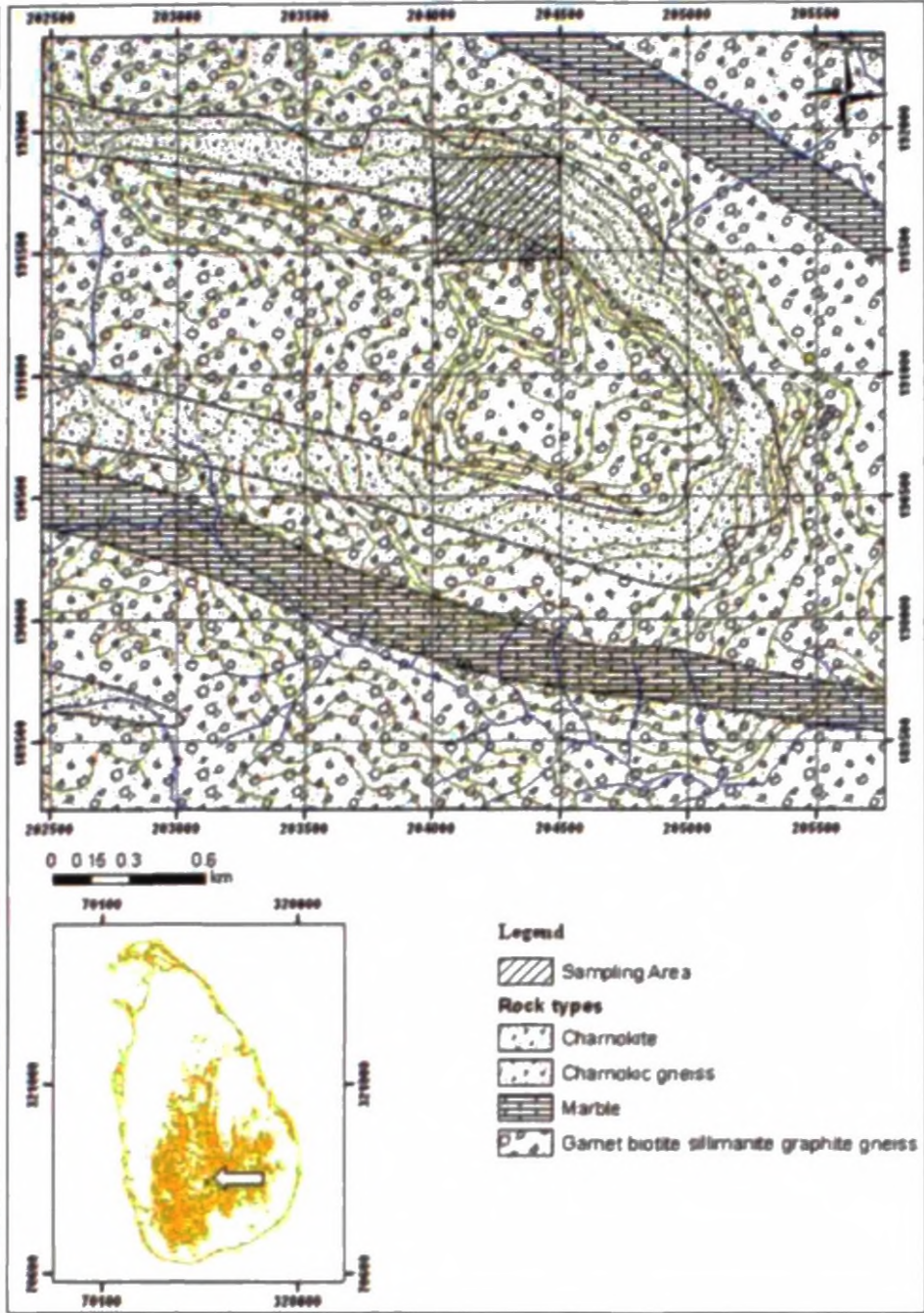


Figure 3: Geology of the study area around Hakgala

Syzygium rotundifolium, *Calophyllum walkeri*, *Cinnamomum ovalifolium*, *Symplocos bractealis* were identified as highly susceptible to forest dieback in the Hakgala SNR (Figure 4).

METHODOLOGY

First Stage

During the first stage, available concentrations of major and micronutrients were measured in soil samples collected from three plots established in (i) healthy areas, (ii) dieback forest on slope areas and (iii) dieback forest on flat areas. Samples were collected from the top horizon, 30 cm and 75 cm depth levels at each corner of the plot.

NH₄-N and NO₃-N of the soil were extracted by 2M KCl. NH₃ and NO₃⁻ in the extract were distilled with MgO and Devarda's alloy, and liberated NH₃ was collected in boric acid. Borate ions in the distillate were titrated against 0.01 HCl solution until the green to pink end point. Na⁺, K⁺, Mg²⁺ and Ca²⁺ were extracted with NH₄O Acetate. Available micronutrients Zn, Cu, Mn, Fe and Ni were determined by extracting the soil with DTPA-

ammonium bicarbonate extract (Soltanpour and Schwab, 1977). Element concentrations in the extractions were measured using atomic absorption spectrophotometer.

Second Stage

Field Sampling; In the second stage, materials were collected from eight plant species having different susceptibilities to dieback. Considering the susceptibility of different species to forest dieback (% of dieback shown in parentheses) reported by Adikaram and Mahaliyanage (1999) from HPNP, individual trees belonging to the species *Symplocos bractealis* (33%), *Syzygium rotundifolium* (35%), *Calophyllum walkeri* (23%), *Cinnamomum ovalifolium* (21%), *Syzygium revolutum* (15%), *Meliosma simplicifolia* (14%), *Nothapodyte foetida* (0%), and *Eugenia mabaeoides* (2%), were selected for the study based on the slope/geology of the area and the extent of dieback of individuals (Figures 3 and 4). Trees with a minimum girth at breast height (GBH) of 10 cm and a height of 1 m were selected for sampling. At least two plants from slopes and one to two plants from flat areas of each and every species were selected for sampling. Altogether 30 plants were sampled. Extent of dieback was categorized as high (90-50%), moderate (50-20%) and healthy (<20%).

About 500 g of plant materials were collected from each and every individual plant and were tightly packed in polythene bags. All the samples were quickly transferred to the laboratory for analysis. Soil samples were collected in relation to the selected

plants. Three different soil samples were collected at each and every location at different directions and at about 1 m distance from the plant. Altogether 90 soil samples were collected at depths from 0 to 50 cm using an augur. The samples were collected and tightly packed in polythene bags to prevent changes in the moisture content.

Chemical Analysis

All soil samples were swiftly analyzed for moisture content, pH and EC (electric conductivity) at the laboratory. Based on the results of the pilot study as well as considering the results of the study by Ranasinghe et al. (2007), soil plant samples were analyzed for available indices of micronutrients (Mn, Fe) and toxic elements (Pb, Al). The available Fe, Mn and Pb were determined by extracting the soil with DTPA (Diethylene Triamine Penta Acetic acid extract). Extractants were analyzed for the above elements by AAS. KCl solution was used to extract available Al content in soil samples. Extracted Al ions were spectrometrically determined by the developing colour with Aluminon-acetate buffer.

Plant samples were digested in nitric- perchloric-sulphuric acid solution. The acid mixture and total contents of Mn, Fe, Pb and Al were determined by AAS. Standard solutions and replicates were analyzed after each batch of 10 samples to measure the accuracy and precision of the instrument. Duplicate soil extract solutions were prepared to quantify the precision of the method. Table 1 shows the accuracy of the measurements in % values and precision as standard deviation.



Figure 4: Dead *Syzygium rotundifolium* tree

Table 1: Quality control results of soil and plant chemical analysis of soils and plants

Element	Soil			Plant		
	Accuracy %	Precision (Stdev)		Accuracy %	Precision (Stdev)	
		Instrument	Method		Instrument	Method
Al	5	.01	0.01	0.02	4.76	0.02
Fe	3	0.32	2.79	2	0.47	0.05
Mn	2	0.02	0.07	5.9	0.02	0.08
Pb	7.7	0.07	0.03	1.6	0.05	0.02

Statistical Analysis

Pearson product moment correlation coefficient was used to identify correlation between dieback stage and soil plant element levels. Also plots of soil/plant element levels Vs. dieback stage for each species were used to extract the relationship between dieback stage and element concentration at species level. Mann Whitney U test was performed to determine any significant difference between extractable soil element levels in slopy areas and flat areas. Kruskal Wallis test was performed using dieback intensity group (High, Medium, Low) as the grouping variable to identify whether there is a significant difference of element levels in plants belonging to different dieback stages.

Also Kruskal Wallis test was performed using plant species as the grouping variable to determine any significant difference of element levels between species.

RESULTS AND DISCUSSION

Field Observations

In the Hakgala SNR, forest dieback is intense (>75%) on slopes (>40°) where the forest is exposed to strong winds. In most of the slope areas the forest has been completely removed leaving a few decomposing stems and allowing *Strobilanthes spp.* to spread over. A similar situation can also be observed on the Thotupola Kanda ridge in the HPNP. However, it was noted that dieback had not affected the plant species in the pygmy forests such as *Osbekia spp.*, *Symplocos elegans*, *Rhodomyrtus tomentosa* and *Vaccinium leschenaultii*. In flat areas, the dieback intensity is generally low (<25%) except in some specific localities where moderate intensities (25-75%) can be observed. Because of strong winds, tree height decreases towards higher altitudes and pygmy forest formations occur in the vicinity of the peaks. Strong winds prevail during the SW monsoonal period shedding a high amount of leaves from the tree canopies in the flat terrain and leaving a thick leaf matter layer on the forest ground. Losing a considerable amount of leaf matter could impose a stress on trees of the area.

Element Concentrations in Soils

Major and Trace Nutrients

Wjesundara (1991), attributed a possible deficiency in available major- and micro- nutrients as the cause for forest dieback. Chandrajith *et al.*, (2009) also recorded higher total and acid extractable Ca levels in healthy forest than in dieback sites. However, results of the first stage and the soil studies in the Hakgala SNR by Jayasekara (1992), no significant depletion or excess (except Fe and Mn) in available concentrations of nutrients, except for low P values reported by Jayasekara (1992). According to first stage results, there is no significant difference between extractable nutrient levels in the unhealthy and the healthy forests (Table 2). The same phenomenon was observed in the tropical montane forests in the HPNP as well (Ranasinghe and Dissanayake, 2003).

Soil Toxicity

High levels of of DTPA extractable Pb Mn, Fe, and KCl extractable Al were observed in Hakgala forest during the first stage of the study. Similar concentrations were reported in relation to dieback distribution in the tropical montane forests of the HPNP (Ranasinghe *et al.*, 2007). Chandrajith *et al.* (2009) reported high Fe, Mn levels in soils of HPNP. Therefore, DTPA extractable levels of Fe, Mn, Al and Pb were measured in the soil around each selected tree.

Aluminium

Extractable aluminium levels in the uppermost 75cm of soils of the first stage sites vary from 36.7 to 122.7 ppm (Table 2). The downward increment of Al levels may indicate underground lithology as the source of Al.

Extractable Al values in second stage sites vary between 0.7 and 390.8 ppm (Table 3). Mann - Whitney test recognizes soil Al in slope and in flat areas at a significant level of 0.1 (Table 4). Extractable soil Al of the area has a positive correlation with slope of the location (Spearman Coefficient 0.31, Sig. = 0.1) (Table 5). Extractable soil Al concentration has a weak positive Spearman correlation with dieback intensity ($r = 0.23$, Sig. = 0.22) (Table 5). Generally, montane forests of Sri Lanka contain high Al contents (Werner 1982, Werner and Balasubramaniam, 1992).

Table 3: Extractable soil element levels at different plant species (Second Stage)

Species	Dieback Category	Slope	Soil Pb/ppm	Soil Al/ppm	Soil Mn/ppm	Soil Fe/ppm
Caw	H	S	1.0	152.3	4.3	190.1
Caw	M	S	1.4	285.4	3.1	173.8
Caw	L	F	0.7	72.5	2.3	103.1
Caw	L	F	1.0	14.8	17.0	220.1
Cov	H	S	1.3	94.1	8.3	149.7
Cov	L	S	0.4	390.8	1.7	113.5
Cov	L	F	0.5	84.8	4.9	48.1
Cov	M	F	0.4	122.6	2.3	223.1
Eu	H	S	1.1	51.1	4.0	171.6
Eu	L	S	0.6	33.3	2.5	61.5
Eu	H	F	0.7	72.5	2.3	103.2
Eu	L	F	1.8	28.1	25.2	98.7
Mes	H	S	1.7	23.1	4.7	252.6
Mes	L	S	1.4	4.4	18.1	141.9
Mes	H	F	1.3	4.5	7.8	166.0
Mes	L	F	1.1	56.0	49.2	172.5
Sre	H	S	1.0	141.6	4.8	144.6
Sre	M	S	1.3	311.0	3.9	133.2
Sre	H	F	1.1	14.4	57.2	89.1
Sre	L	S	1.0	17.4	40.2	171.2
Sro	L	F	1.2	0.7	21.8	50.5
Sro	H	S	1.4	7.4	6.8	110.1
Sro	H	S	1.5	134.6	4.5	150.5
Sro	L	S	1.2	15.3	25.0	372.1
Syb	H	S	1.4	249.2	2.8	102.6
Syb	L	S	1.7	88.1	6.9	102.7
Syb	L	S	2.4	22.5	27.5	121.7
Nf	L	F	0.6	39.4	3.5	64.9
Nf	L	S	1.1	5.5	8.0	196.4
Nf	H	F	1.0	3.8	4.0	65.0

Caw - <i>Calophyllum walker</i>	Cov - <i>Cinnamomum ovalifolium</i>	Eu - <i>Eugenia mabaeoides</i>
Eu - <i>Eugenia mabaeoides</i>	Mes - <i>Meliosma simplicifolia</i>	Sre - <i>Syzygium revolutum</i>
Sro - <i>Syzygium rotundifolium</i>	Syb - <i>Symplocos bractealis</i>	Nf - <i>Nothapodytes foetida</i>

H - High	M - Medium	L - Low	S - Slope	F - Flat
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Table 4: Results of the Mann-Whitney test for soil element data

	Soil Pb/ppm	Soil Al/ppm	Soil Mn/ppm	Soil Fe/ppm
Mann-Whitney U	59.5	69	100.5	66
Wilcoxon W	137.5	147	271.5	144
Z	-2.06	-1.65	-0.32	-1.78
Asymp. Sig. (2-tailed)	0.04	0.10	0.75	0.08
Exact Sig. [2*(1-tailed Sig.)]	0.039(a)	0.104(a)	0.755(a)	0.079(a)

a. Not corrected for ties.
b. Grouping Variable: slope

Also when the soil is under continuously poor aeration, high Fe concentration may limit the absorption capacity of available N. Therefore, even though no direct relationship could be observed amongst extractable soil Fe level, leaf Fe level and dieback intensity, impact of Fe toxicity on forest health cannot be excluded.

Manganese

First stage sites report 11.4 - 33.2 ppm extractable Mn concentrations for soil depths varying from 0-75

were reported from the slopes of Thotupolakanda and Kirigalpotta ridges (Ranasinghe *et al.*, 2007). Mann-Whitney test shows no evidence to suggest that soil Pb values on slope and flat areas belong to the same population (Table 4). Chandrajith *et al.* (2009) reported 14-29 ppm acid extractable Fe concentration from HPNP. Ranawana *et al.* (2007) reported total Pb values ranging from 16.5 - 29 ppm from dieback and healthy forests sites in the HPNP. It was also reported that most of the Pb in soils were in acid leachable form. Hence, these authors concluded that most of

Table 5: Pearson product moment correlation coefficient matrix for soil data

Element		Soil Pb ppm	Soil Al ppm	Soil Mn ppm	Soil Fe ppm	Dieback %	slope
Soil Pb	Correlation Coefficient	1.00	-0.14	0.44	0.13	0.12	0.38
	Sig. (2-tailed)		0.45	0.02	0.50	0.54	0.04
Soil Al	Correlation Coefficient	-0.14	1.00	-0.57	0.09	0.23	0.31
	Sig. (2-tailed)	0.45		0.00	0.65	0.22	0.10
Soil Mn	Correlation Coefficient	0.44	-0.57	1.00	0.11	-0.20	-0.06
	Sig. (2-tailed)	0.02	0.00		0.55	0.29	0.76
Soil Fe	Correlation Coefficient	0.13	0.09	0.11	1.00	0.25	0.33
	Sig. (2-tailed)	0.50	0.65	0.55		0.19	0.07
Die %	Correlation Coefficient	0.12	0.23	-0.20	0.25	1.00	0.18
	Sig. (2-tailed)	0.54	0.22	0.29	0.19		0.35
slope	Correlation Coefficient	0.38	0.31	-0.06	0.33	0.18	1.00
	Sig. (2-tailed)	0.04	0.10	0.76	0.07	0.35	

cm (Table 2). There is a clear decrease of Mn levels with depth.

Sites of the Second stage report DTPA extractable Mn levels varying from 1.7 ppm to 57.2 ppm (Table 3). Jayasekara (1992) reported 126.5 ppm, an average Mn level from the top 60 cm soil layer of the Hakgala SNR. Chandrajith *et al.* (2009) recorded 19-197 ppm acid extractable Mn and 0.026 - 0.45 % total MnO concentration from HPNP. Unlike Pb, Al and Fe, soil Mn level does not show a significant correlation with slope (Table 5). Soil acidification enhances the solubility of Mn (Fernandez, 1989, Kitao *et al.*, 2001). Mn toxicity generally occurs at pH values less than 5 (Foy *et al.*, 1978 and 1988). Toxicity threshold of Mn varies for different plant species. For seedlings of *Agathis australis*, this threshold is as low as 2.5 ppm (Peterson, 1962).

Lead

First Stage study recorded DTPA extractable Pb values of 1.7 - 3.2 ppm from the top soils. Sites of the second stage report DTPA extractable Pb concentrations varying between 0.6 - 2.4 ppm (Table 3). Extractable soil Pb levels show a significant correlation with slope (Spearman coefficient 0.38) indicating high Pb contents on the slope areas (Table 5). A similar situation was observed in the HPNP where higher concentrations (>1.5 ppm) of soil Pb

the Pb in soils was loosely bound, and accordingly, an anthropogenic origin was proposed. As no specific rock can be considered as the source of Pb in the area, strong monsoonal winds are believed to have brought Pb from the industrialized SW area and deposited the same on slopes of the ridges. Extractable soil Pb values in several relatively polluted and unpolluted sites around the country show that high values represent polluted sites. DTPA extractable Pb levels in Ohio farm soils range from 1.5 to 7.7 ppm whereas total values range from 9 to 39 ppm (Logan and Miller, 2007). Average concentration values in the world vary from 2 to 200 ppm (Baker and Chesnin, 1975). Impact of elevated extractable exotic Pb levels on the healthy forests cannot be assessed directly, as the toxicity thresholds for delicate endemic montane forest plant species are not known.

Element Concentrations in Plant Matter

Due to practical considerations, concentrations of Al, Pb, Fe and Mn in plants were assessed using plant leaves, even though certain elements tend to concentrate in the root. Both plant samples in selected trees and soil samples in the immediate vicinity were studied in order to study the relationship between element concentrations in plants and soil.

Aluminium

Leaf aluminium levels in plants studied vary widely, ranging between 18.9 to 20047 ppm (Table 6). No significant relationship between soil Al level and leaf Al level could be observed (Figure 5a). *Syzygium rotundifolium*, *Calophyllum walkeri* and, *Cinnamomum ovalifolium* which are highly susceptible to dieback, show increasing concentration of Al has a relationship with dieback intensity. It is noteworthy that regardless of the dieback extent, all *Symplocos bractealis* trees have abnormally high Al values exceeding 7000 ppm (Figure 5). One *Eugenia mabaeoides* tree also showed 20047 ppm on total leaf Al concentration. Jayasekara (1992) reported Al concentrations lying between 54 to 148 ppm in six species including *Eugenia mabaeoides* which had a mean value of 148 ppm.

Reported mean Al level from the undergrowth at the Hakgala SNR is 12800 ppm (Jayasekara 1992). Leaf Al levels show a significant positive correlations with soil Al levels (Spearman rank coefficient 0.54). Also leaf Al levels shows significant positive correlation with leaf Fe and Mn levels (sig. <0.05). But they do not show a linear relationship with dieback intensity (Table 7). Kruskal Wallis test could not recognize a significant difference between dieback intensity groups and species with respect to leaf Al level (Table 8). Truman *et al.* (1986) specified 800 ppm for *Pinus radiata*, and for more sensitive species, 32 ppm value has been proposed by Steinen and Bauch (1988). Álvarez *et al.* (2005) found that leaf Al level varied greatly within the same species. They reported foliage Al levels higher than 800 ppm in all species growing on granodiorite soils indicating possible existence of Al stress.

The most prominent symptoms of Al toxicity in plants are the inhibition of root growth and unhealthy roots which generally lead to deficiencies of nutrients such as P, K, Ca and Mg (Haug and Vitorello, 1996). Symptoms manifested in the shoots are usually regarded as a consequence of injuries to the root system (Vitorello *et al.*, 2005). However, Adikaram and Mahaliyanage (1999) reported healthy root systems of dying trees in the HPNP, where similar extractable Al levels and pH levels are reported (Ranasinghe *et al.*, 2007). Jayasekara (1992) also

reported the absence of such significant deficiency of nutrients in plants in the Hakgala SNR.

It has been known for a long time that many plant species show wide variability with respect to their resistance to Al toxicity (Vitorello *et al.* 2005). As such, there is a strong possibility for developing a resistance in these plants to high Al levels having a geological origin, unless there is a sudden increase of dissolution due to soil acidification caused by acid rains.

Iron

Iron concentration in leaves of the studied plants varies between 47.5 to 800 ppm (Table 6). Figures 6(a) and 6(b) clearly show that Fe levels in plant leaves do not depend on the levels in soil. Dying plants of *Syzygium rotundifolium*, *Calophyllum walkeri* and *Cinnamomum ovalifolium* have high Fe contents (Figure 6). It shows a significant correlation with leaf Al contents (Spearman coefficient is 0.61). The Spearman correlation coefficient between dieback intensity and leaf Fe content is 0.36 (sig. 0.06) (Table 7). Kruskal – Wallis test does not recognize differences between dieback groups or species based on leaf Fe contents (Table 8).

Jayasekara (1992) reported mean leaf Fe concentrations from 94 to 169 ppm on 6 different plant species in Hakgala. Chandrajith *et al.* (2009) recorded Fe levels of 52.9 to 157 ppm in *Calophyllum walkeri* leaves, 63 to 426 ppm in *Syzygium rotundifolium* leaves and 65 to 270 ppm in *Cinnamomum ovalifolium* leaves in HPNP. The toxicity threshold of Fe in plants varies widely depending on the species. *Glyceria fluitans* having 100.5 ppm Fe in shoots does not show toxicity symptoms whereas affected plants have Fe levels of 1131 ppm (Lucassen *et al.*, 2000). Fe uptake in plants is highly regulated to prevent excess accumulation (Kim and Guerinot 2007). Lack of significant correlation between soil Fe and leaf Fe levels can be due to the regulating of Fe uptake. As such, dieback caused by Fe toxicity is unlikely.

Table 6: Total element concentrations in plant leaves

Species	Dieback Category	Slope	Leaf Pb/ppm	Leaf Al/ppm	Leaf Mn/ppm	Leaf Fe/ppm
Caw	H	S	9.9	568.4	36.5	409.5
Caw	M	S	32.1	385.1	22.7	588.0
Caw	L	F	2.2	67.6	15.8	113.1
Caw	L	F	11.8	53.9	12.7	96.6
Cov	H	S	19.8	452.8	271.8	355.4
Cov	L	S	10.0	125.2	357.0	124.5
Cov	L	F	15.3	56.0	91.9	180.4
Cov	M	F	16.9	745.4	241.9	160.3
Eu	H	S	21.7	62.3	110.6	380.7
Eu	L	S	22.1	20047.6	85.6	800.8
Eu	H	F	7.2	115.2	17.9	193.9
Eu	L	F	36.3	150.7	15.8	78.7
Mes	H	S	8.7	72.0	25.7	66.9
Mes	L	S	9.6	31.3	45.7	47.5
Mes	H	F	12.6	55.1	32.8	310.6
Mes	L	F	22.1	163.4	49.6	186.8
Sre	H	S	6.6	148.2	115.8	143.0
Sre	M	S	14.6	326.7	59.4	258.2
Sre	H	F	9.7	25.8	17.1	55.1
Sre	L	S	13.7	18.9	26.9	49.2
Sro	L	F	4.2	60.6	53.9	112.1
Sro	H	S	11.5	178.6	57.5	132.0
Sro	H	S	24.9	101.6	112.4	201.0
Sro	L	S	14.2	85.1	113.0	79.2
Syb	H	S	10.1	7472.1	288.9	141.0
Syb	L	S	8.8	18878.1	105.7	466.8
Syb	L	S	28.8	18821.3	55.2	129.2
Nf	L	F	15.9	57.3	19.5	111.5
Nf	L	S	1.1	5.5	8.0	196.4
Nf	H	F	1.0	3.8	4.0	65.0

Caw - *Calophyllum walkeri*Cov - *Cinnamomum ovalifolium*Eu - *Eugenia mabaeoides*Eu - *Eugenia mabaeoides*Mes - *Meliosma simplicifolia*Sre - *Syzygium revolutum*Sro - *Syzygium rotundifolium*Syb - *Symplocos bractealis*Nf - *Nothapodytes foetida*

H - High

M - Medium

L - Low

S - Slope

F - Flat

Table 7: Pearson product moment correlation coefficient matrix for plant element levels.

Soil Pb/ppm	Soil Al/ppm	Soil Mn/ppm	Soil Fe/ppm	Leaf Pb/ppm	Leaf Al/ppm	Leaf Mn/ppm	Leaf Fe/ppm
0.17	0.14	0.11	0.14	1.00	0.29	0.12	0.30
0.38	0.47	0.57	0.47	n.d.	0.13	0.55	0.12
0.21	0.55	-0.33	-0.01	0.29	1.00	0.45	0.61
0.28	0.00	0.08	0.97	0.13	n.d.	0.02	0.00
-0.05	0.45	-0.23	0.05	0.12	0.45	1.00	0.35
0.82	0.02	0.23	0.79	0.55	0.02	n.d.	0.07
-0.04	0.54	-0.43	0.04	0.30	0.61	0.35	1.00
0.83	0.00	0.02	0.84	0.12	0.00	0.07	n.d.

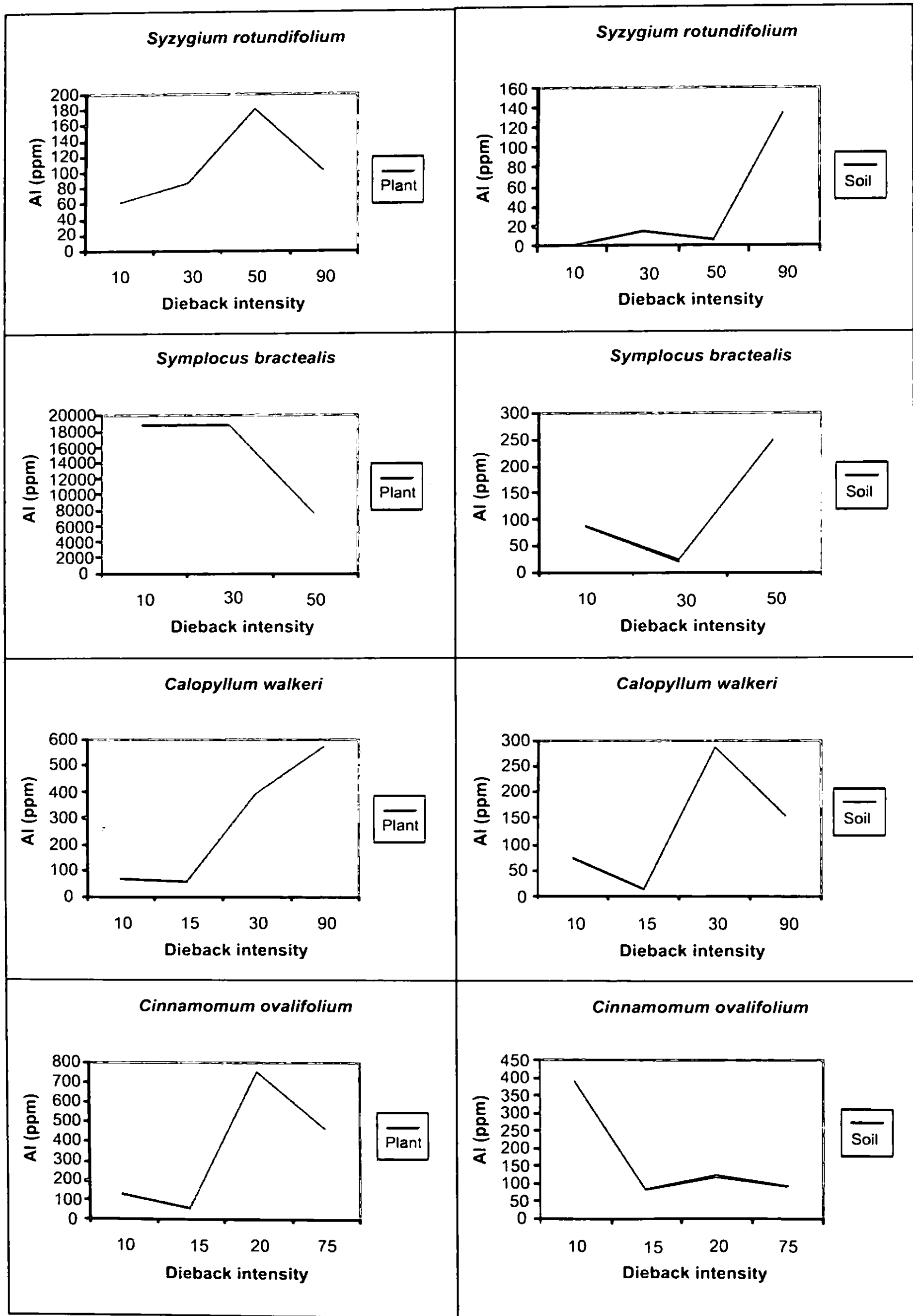


Figure 5 a: Plot of Al concentration (in ppm) in the plant vs. its dieback stage

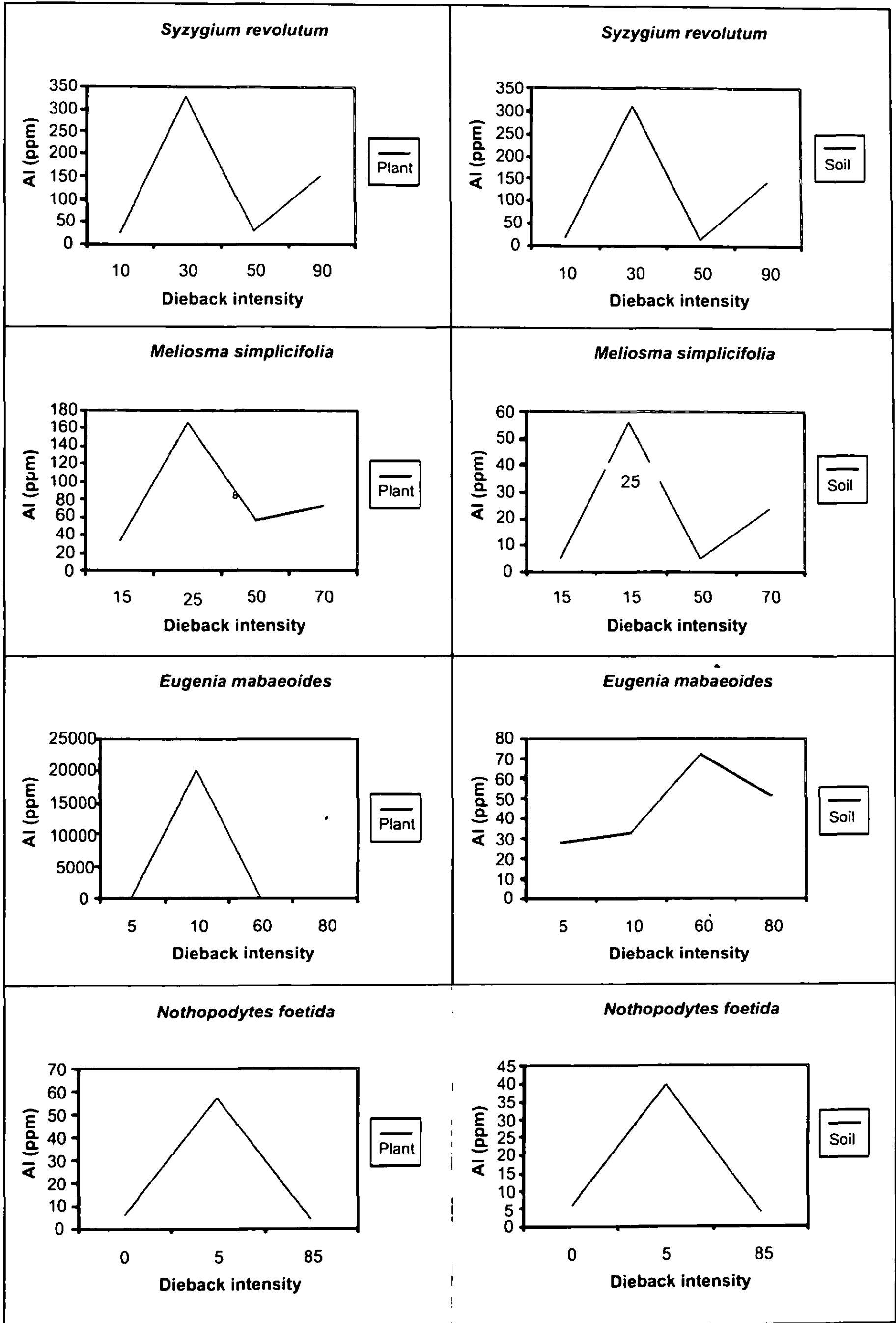


Figure 5b: Plot of Al concentration (in ppm) in the plant vs. its dieback stage

Manganese

Leaf Mn concentration of Hakgala plants varies from 4.0 to 357 ppm (Table 6). Mn contents in leaves are higher in dying trees of *Symplocos bractealis*, *Calophyllum walkeri*, and *Syzygium revolutum* (Figure 7). However, the variation of Mn levels in soil and leaves of plant at different dieback stages show that Mn in plants does not depend on the soil level (Figure 8). Mn shows a significant positive correlation with leaf Al content (spearman coefficient 0.45) (Table 7). Kruskal-Wallis test recognizes differences between species based on leaf Mn concentrations (Table 8). Critical toxicity levels of Mn in leaves vary in a wide range due to the large differences in Mn tolerance. Critical leaf Mn levels of six crop species ranging from 160 to 7100 ppm have been presented by El Jaoual and Cox (1998). Excess available concentration of Mn can interfere with absorption and utilization of other elements such as Ca, Mg, P and Fe. However, no such significant deficiency in these elements in leaf matter has been observed in Hakgala plants by Jayasekara (1992).

Chandrajith *et al.* (2009) record Mn levels of 16.8 to 70.5 ppm in *Calophyllum walkeri* leaves, 19.6 to 70 ppm in *Syzygium rotundifolium* leaves and 1.45 to 3.31 ppm in *Cinnamomum ovalifolium* leaves from the HPNP. No significant deficiency in Ca, Mg, and Fe levels in plant matter from dead and healthy trees in the HPNP was reported in the results of Ranawana *et al.* (2007). Mn toxicity displays initial symptoms such as marginal chlorosis and necrosis on leaves, and later, roots become brown after the shoots are severely injured at critical stages. However, no such symptoms were observed in dead or dying plants in the Hakgala or dieback sites in HPNP during the detailed plant pathological study related to forest dieback (Adikaram and Mahaliyanage, 1999). Even though high Mn levels could impose stresses on

certain plants, Mn toxicity cannot be recognized as the root cause for unhealthy forests in Sri Lanka.

Lead

Mean Pb levels in leaves of the studied plant species vary from 2.2 to 36.3 ppm (Table 6). Out of the four *Eugenia mabaeoides* trees studied, three of the leaf Pb levels exceed 20 ppm. Pb level in soil seems to be controlled by the available Pb concentration in soil (Figure 8). Pb levels do not show a significant correlation with the dieback intensity (Table 7). Also Kruskal-Wallis test could not significantly recognize the differences between dieback groups and species based on leaf Pb (Table 8). However, leaf Pb increases with dieback stage in *Calophyllum walkeri*, *Cinnamomum ovalifolium* and *Syzygium rotundifolium* (Figure 8).

Chandrajith *et al.* (2009) recorded Pb levels of 2.06 to 5.73 ppm in *Calophyllum walkeri* leaves, 1.52 to 4.74 ppm in *Syzygium rotundifolium* leaves and 1.45 to 3.31 ppm in *Cinnamomum ovalifolium* leaves from the HPNP. These values are considerably lower than those recorded in Hakgala for the same plants species; *Calophyllum walkeri* (2.2 to 32.1 ppm), *Syzygium rotundifolium* (4.2 to 24.9 ppm) *Cinnamomum ovalifolium* (10 to 19.8 ppm). Bowen (1979) reported Pb levels between 2 to 8 ppm in land plants. Leaf Pb levels varying from 3 to 16 ppm have been reported from Bavarian and Austrian Alps, whereas values varying from 0.3 to 18 ppm have been reported from cereals and vegetables grown very close to highways in Canada (Wedepohl, 1978). Heliotis and Karandinos (1988) recorded leaf Pb levels of 82.8 ppm in *Pseudevernia furfuracea* grown on Mont Parnés, about 30 km outside the city centre of Athens, Greece.

Table 8: Kruskal-Wallis test results for plant element data.

	Leaf Pb	Leaf Al	Leaf Mn	Leaf Fe
Chi-Square	1.74	0.23	2.75	5.56
df	2.00	2.00	2.00	2.00
Asymp. Sig.	0.42	0.89	0.25	0.06
Grouping Variable: Dieback intensity groups (High, Medium, Low)				
	Leaf Pb	Leaf Al	Leaf Mn	Leaf Fe
Chi-Square	2.94	9.71	15.21	4.29
df	6	6	6	6
Asymp. Sig.	0.82	0.14	0.02	0.64
Grouping Variable: Species				

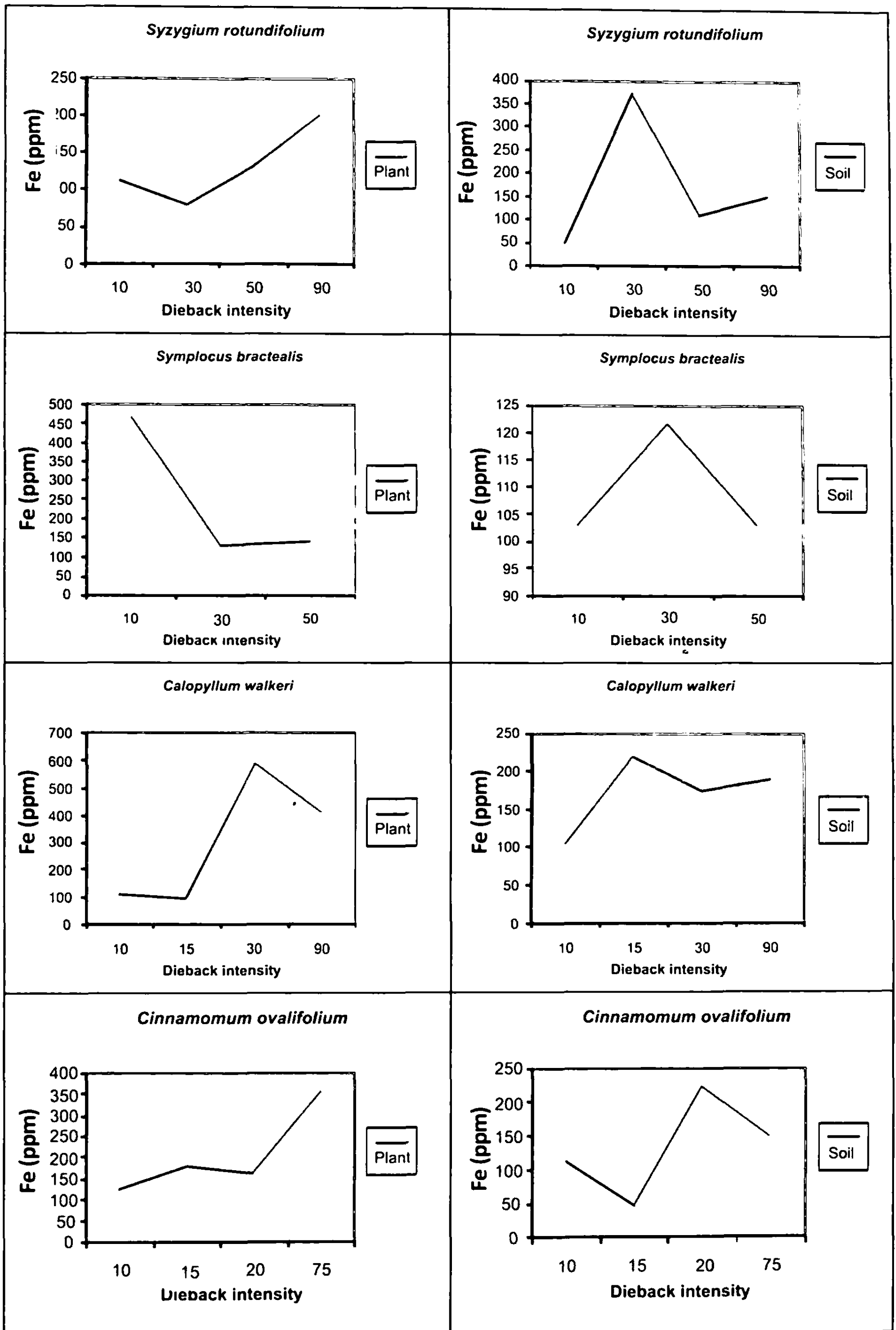


Figure 6(a): Plot of Fe concentration (in ppm) in the plant vs. its dieback stage

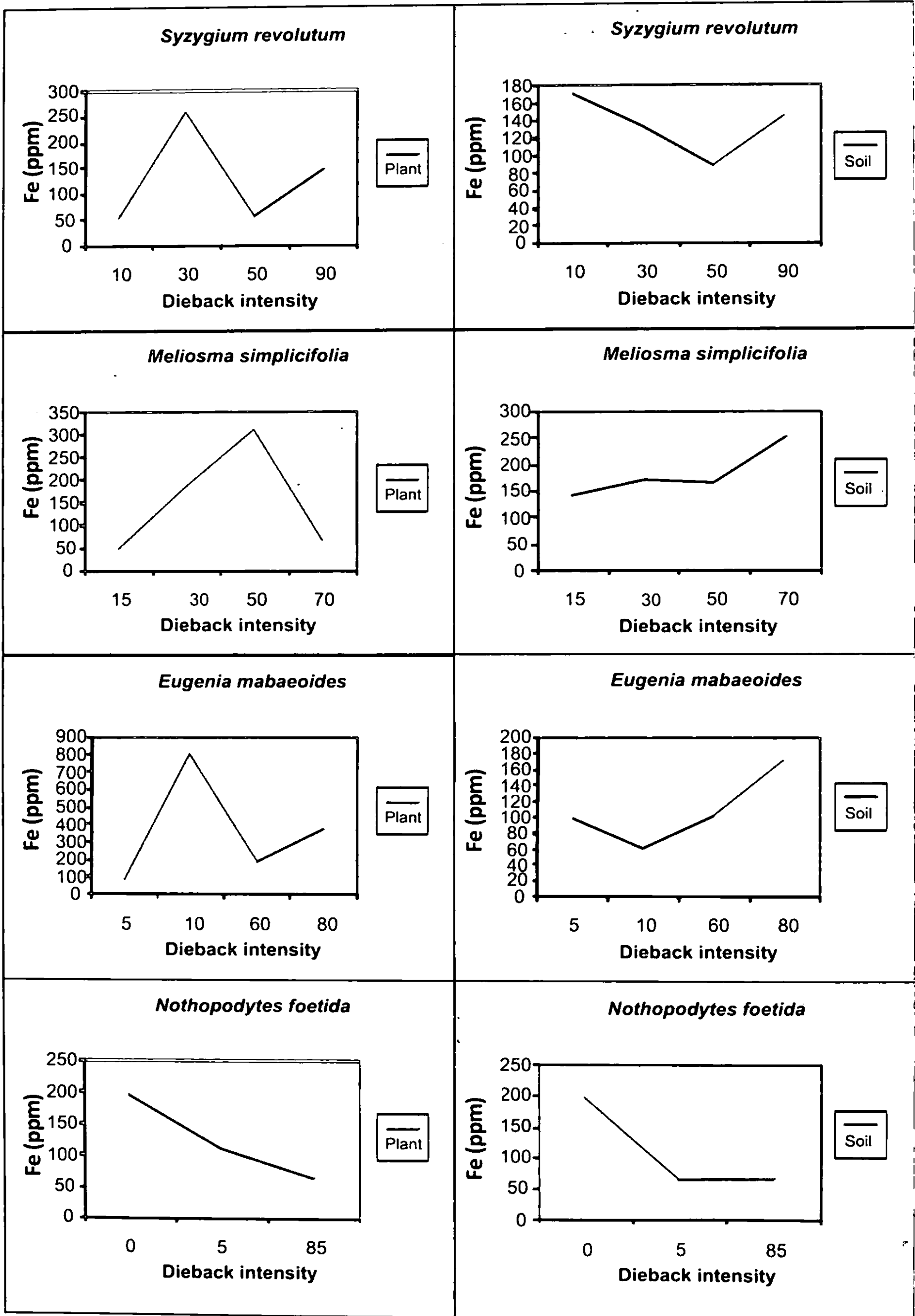


Figure 6(b): Plot of Fe concentration (in ppm) in the plant vs. its dieback stage

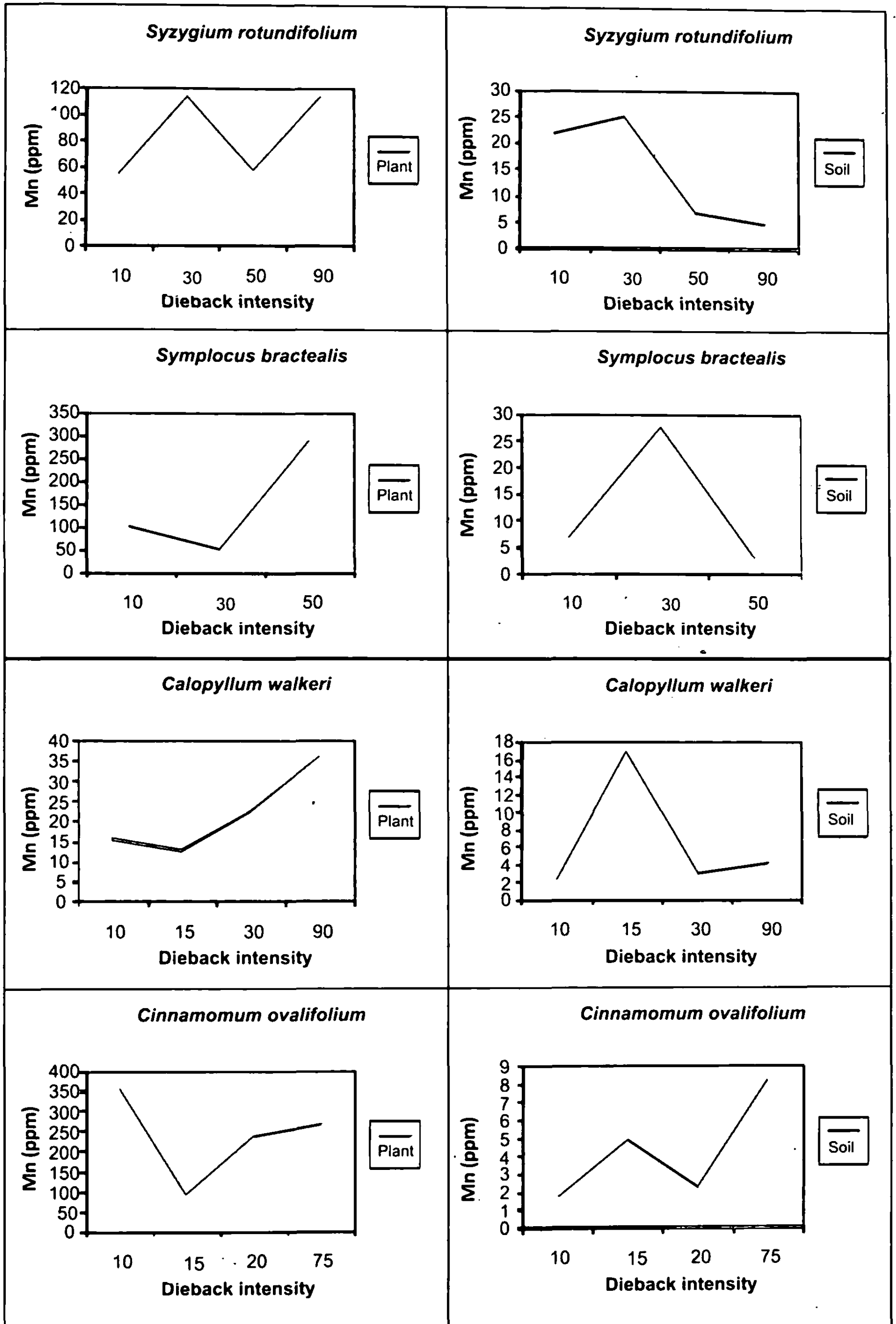


Figure 7a: Plot of Mn concentration (in ppm) in the plant vs. its dieback stage

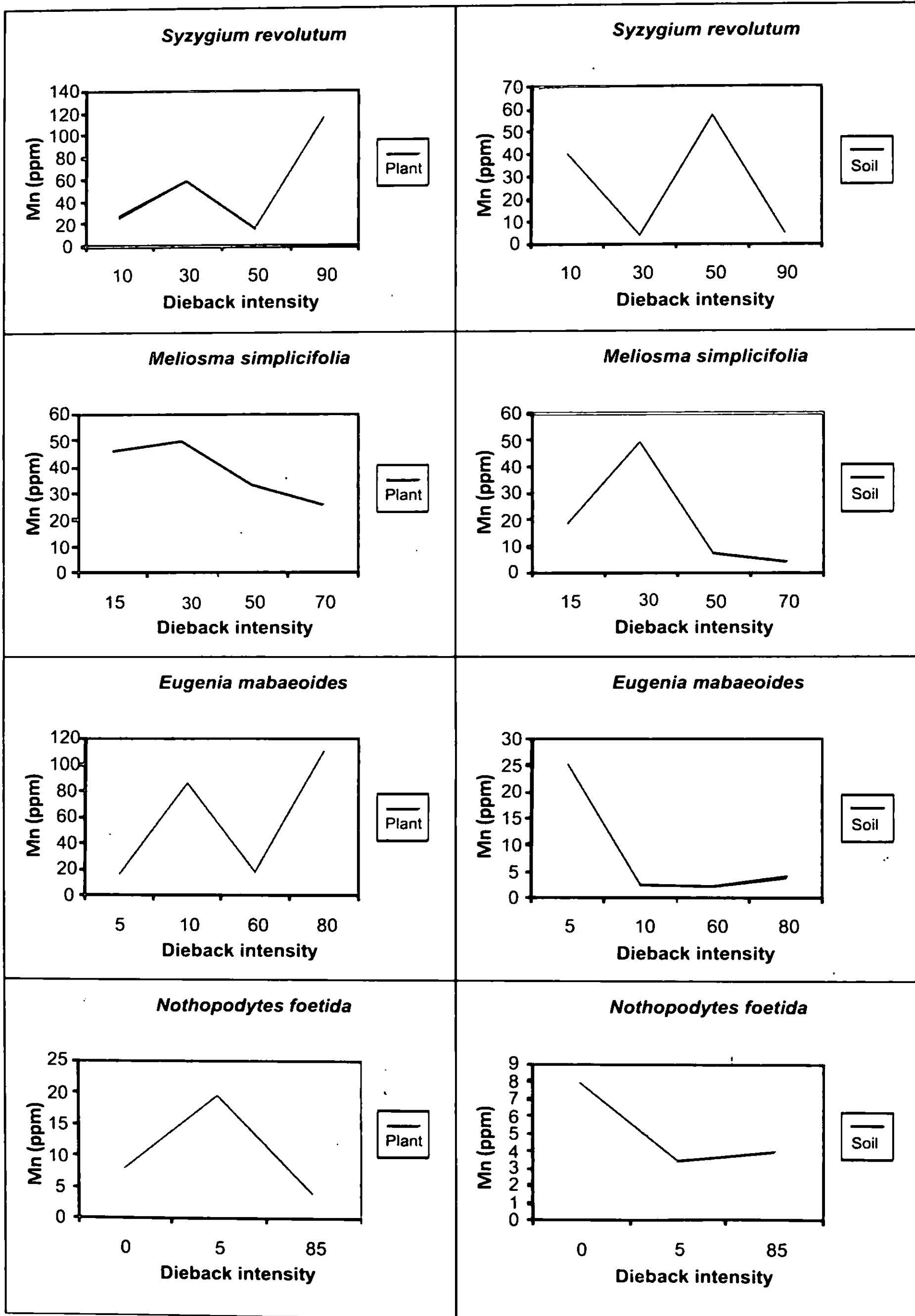


Figure 7b: Plot of Mn concentration (in ppm) in the plant vs. its dieback stage. Continued..

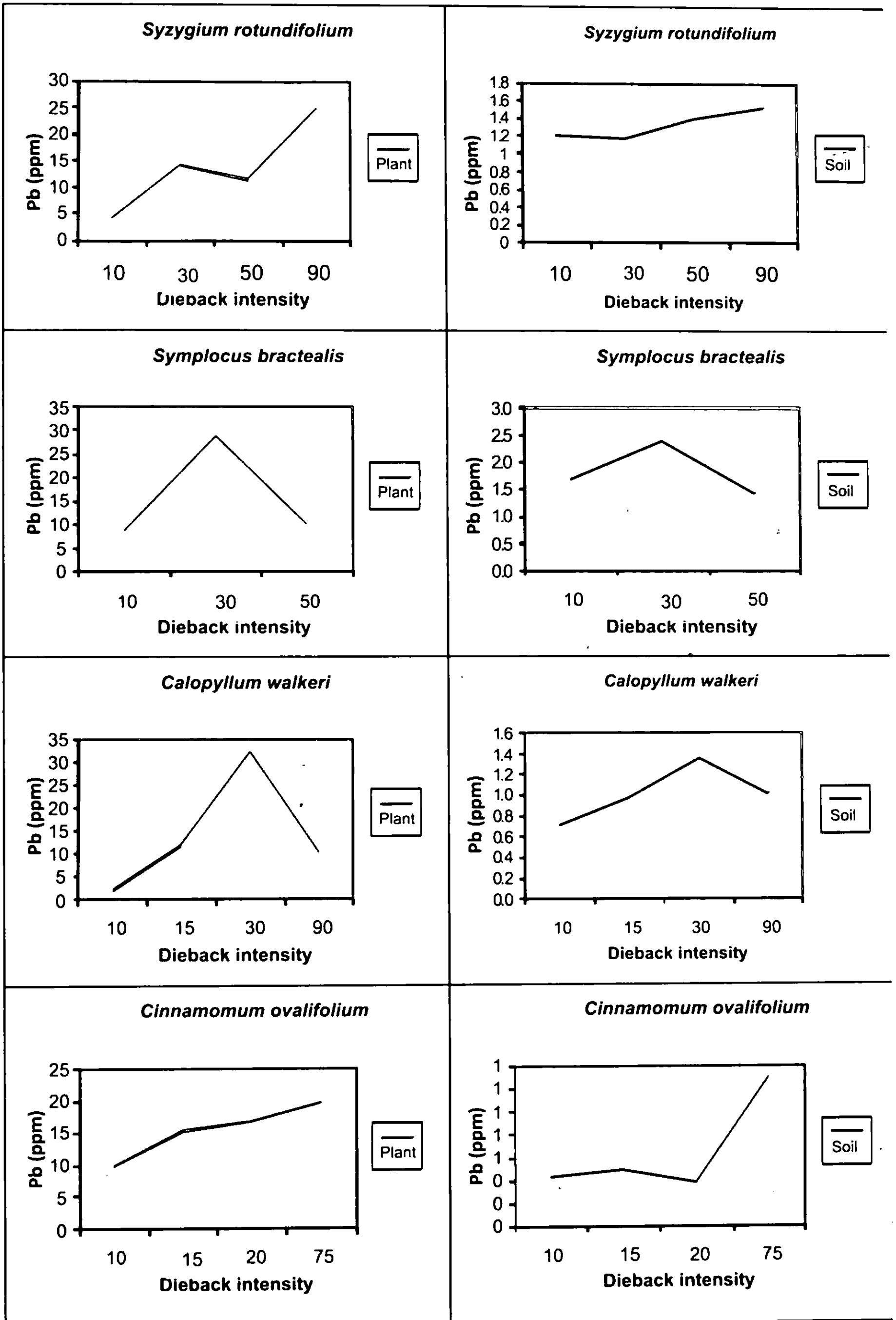


Figure 8a: Plot of Pb concentration (in ppm) in the plant vs. its dieback stage

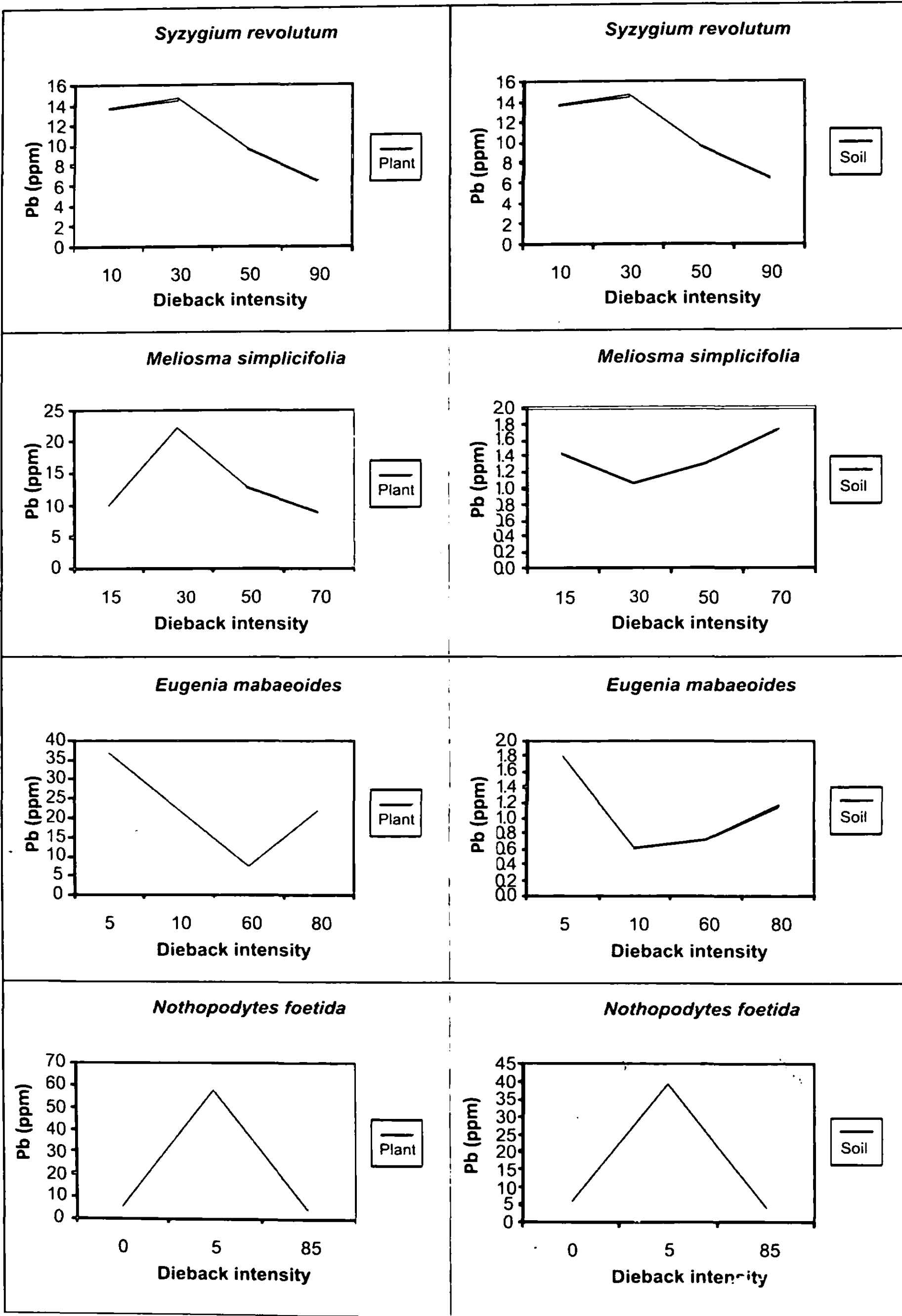


Figure 8b: Plot of Pb concentration (in ppm) in the plant vs. its dieback stage; Continued..

Chandrajith *et al.* (2009) suggested that air pollution could be contributing to the decline of forests in the area. Aksoy and Şahin (1999) reported values of 180.21, 75.82, 50.56 and 16.81 ppm total leaf Pb levels in unwashed *Elaeagnus angustifolia* from industrial, roadside, urban and rural locations respectively. Washed samples from the same sites recorded values of 65.2, 35.25, 28.38 and 15.4 ppm. Hauck *et al.* (2001) have reported a mean value of 179.02 ± 80.6 mg/kg dry wt. from bark in the healthy forest and 130.9 ± 111.9 mg/kg dry wt. from those in the dieback forest on the Harz Mountains in Germany. Haiyan and Stuanes (2003) reported mean total Pb contents ranging from 9.8 to 30.6 ppm dry wt. in cabbage and 0.01 to 1.5 ppm dry wt. in rice grown on soils with total Pb contents of 209.7 to 262.2 ppm in an industrial area of the Hunan province, China, during the period 1991-1997.

Concentrations of total leaf Pb levels at three selected sites with different pollution levels were determined for comparison. Results show that Pb concentrations at Hakgala are almost similar to those of the Homagama location, which is 250 m away from the main traffic road and also near a large newspaper printing press. Total Pb level in *Syzygium* sp. at Dehiwala site, which is 50 m away from a heavy traffic road, varied between 3.4 to 9.8 ppm and Pb concentration of *Ixora* sp., ranged between 4.5 to 6.1 ppm. Concentration of total Pb levels of roots of the same *Syzygium* plant at the Dehiwala site was 17 ppm. However, banning of use of leaded gasoline in 2002 in Sri Lanka must have a significant impact on the leaf Pb content of the young trees tested at the Dehiwala road side site. But Jayasekara and Rossbach (1996) reported Pb levels of 0.29 to 1.1 ppm from about 1 kg plant material each from a higher plant (*Actinodaphne*) a epiphytic orchid (*Bulbophyllum*), of an epiphytic fern and 3.19 to 4.26 ppm from a lichen (*Usnea*) and a bryophyte (*Pogonatum*). However, the dieback status of the host plants of these epiphytes is important because epiphytic lichens are exposed to lower doses of air pollutants in dieback affected forests than intact ones due to lower intercepting surfaces and direct contact with incident precipitation (Hauck and Raunge 2001). Reduction of 40-50% of Pb levels in washed samples from the Hakgala SNR (Jayasekara and Rossbach, 1996) is clear evidence for contribution of atmospheric pollution to plant Pb levels in 1996, six years before banning the use of unleaded gasoline.

The insignificant reduction of Pb levels in washed plant samples of this study, which was carried out four years after the banning of leaded gasoline, further validates the occurrences of said phenomenon. As such, high Pb recorded in plant leaves during this study (carried out 4 years after the banning of leaded gasoline) should have been absorbed from the soil and subsequently accumulated in leaves.

Even though Pb levels in some plants in Hakgala are well above the normal Pb range of 2 to 8 ppm given by Bowen (1979), they are not as high as some of the polluted sites mentioned earlier. Pb uptake studies have shown that roots have an ability to take up significant quantities of Pb while greatly restricting its translocation to above ground parts. In general, the apparent concentration of Pb in aerial parts of the plants decreases as the distance from the root increases (Sharma and Dubey 2005). As such there can be a higher Pb level in the root systems of these plants, which were not evaluated during this study. Pb toxicity in plants can cause a wide variation of disorders such as stunted growth, inhibition of root growth, chlorosis, inhibition of photosynthesis and seed germination and upsetting the mineral nutrient and water balance. However, as mentioned above, healthy root systems were observed in dying and healthy trees in the HPNP by Adikaram and Mahaliyanage (1996). Nutrition experiments have demonstrated that many plants responded to increasing Pb availability to a very limited extent unless aerial Pb was a major factor (Wedepohl, 1978). Even though no direct relationship between dieback intensity and leaf Pb level could be established, the presence of high leaf Pb levels in certain individuals and species, increased dieback intensity on slope areas.

Higher extractable soil Pb content on slope areas, all further validate the hypothesis put forward by Ranasinghe *et al.* (2007) of the possible Pb toxicity to certain sensitive unique plants in montane forests of Sri Lanka. Considering the fact that Pb accumulation is highest in the root system and toxic effects and tolerance levels depend on individual and species level physiological factors, the absence of a direct correlation between leaf Pb level and forest dieback is not a valid argument to discard the possible toxic effects on certain plants. As discussed earlier, the ratio of acid leachable and total soil Pb contents in Horton Plains as well as the ratio between total leaf Pb contents in washed and unwashed samples clearly proves an air borne pollution related Pb deposition in the area prior to the banning of leaded gasoline use in Sri Lanka.

Use of leaded petroleum as fuels until recently has resulted in considerable Pb pollution in stream sediments in Colombo and its suburbs (2 to 583 ppm) (Ranasinghe *et al.*, 2007) as well as in cities close to Hakgala (total Pb level of 65 to 92 ppm in stream sediments) (Ranasinghe *et al.*, 2007). Therefore the emissions from vehicles are a likely major source of Pb in the montane forest areas of the country. Even though the literature recognizes Pb as an element readily deposited close to highways, ability of strong SW monsoonal winds blowing from the highly populated area of Colombo and suburbs, situated at about 100 km from Hakgala, to transport Pb cannot be excluded without further investigations. Erel *et al.*

(2002) have found that the load of foreign atmospheric Pb in Jerusalem, which was brought there by transboundary migration of atmospheric Pb from Egypt, Turkey, and Eastern Europe, is similar to the average local atmospheric Pb in the area. The possible impact of atmospheric Pb transport to the central highlands of Sri Lanka from industrialized south India has also to be investigated. As discussed by Hauck and Runge, (1999), if air pollution is the main source of Pb in plants, modification of Pb levels could be expected with the death of plant due to reduction of the intercepting area and exposure to direct precipitation, which aids removal of Pb from the plant surface. Leaf morphology would play a key role in retaining such air borne Pb, and therefore it may also be responsible for the irregular high and low Pb concentrations recorded from different species.

Pot experiments at similar pH levels and different Pb and Al concentrations to recognize the tolerance and sensitivity of highly susceptible species to forest dieback would be very important to accept or exclude the possible contribution of these elements to the forest dieback in Sri Lanka.

CONCLUSIONS

Field observations of this study indicated that forest dieback was significantly higher in slope areas of the Hakgala SNR facing strong winds. Also it was noticed that strong monsoonal winds impact the forest canopy by causing the shedding of a considerable amount of plant leaves. This study proves the presence of high extractable Mn, Fe, Al and Pb levels in upper montane forests of Hakgala SNR. It is noteworthy to record higher extractable Pb and Al values on slopes, where the dieback is more intense than on flat areas. Except for some individual species, no common significant correlation could be observed between intensity of unhealthiness and any of the studied elements. The study found toxic levels of Al and Pb in plant leaves of certain species.

Both leaf Fe and Mn contents do not show any significant relationship with unhealthiness. Also there is no possible mechanism to explain the enhancement of toxic effect of Mn and Fe derived from underlying rocks which triggers the forest dieback during the last three to four decades. Further, plants do not show symptoms related to Mn and Fe toxicity. Although no direct common relationship between leaf Al level and health of the studied plants could be established, stresses imposed on plants by high Al contents in trees and soils cannot be neglected. The high Al contents in the leaves of dying plants belonging to the most dieback susceptible species is a clue for possible Al toxicity. Increased soil acidity (pH 4.4 to 5.7) can trigger the dissolution of toxic Al^{+3} ions in underlying rocks and soils to make them readily

available for uptake by plants. Also the impact of the recorded toxic concentrations of Pb in plants cannot be ruled out even though there is no direct common relationship between plant Pb levels and dieback intensity, which could be expected due to modification of Pb absorption in plants after the commencement of dying back process. However, an increase in Pb levels in *Calophyllum walkeri*, *Cinnamomum ovalifolium* and *Syzigium rotundifolium* which are highly susceptible for dieback is noteworthy. Such an increase could not be observed in plants belonging to low dieback susceptible species. Increased Pb levels in soils on slope areas, differences between total and extractable soil Pb levels, amounts of washable Pb levels on plant leaves before and after the banning of Pb containing gasoline usage and Pb levels in plants from different parts of the country suggest air pollution as the main Pb source in montane forests. Strong monsoonal winds as well as transboundary effects could be responsible for bringing Pb from the industrialized western province of the country. Also there is a possibility of Pb transport from industrialized South Indian cities. Pot studies are suggested as the next step for dieback research to understand the toxic threshold levels of different plant species for Al and Pb. Further studies have to be carried out to identify the atmospheric pollutant sources.

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