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ENVIRONMENTAL INTERPOLATION MODEL OF VEGETATION DISTRIBUTION PATTERN AND ECOLOGICAL RESTORATION OF DEGRADED LANDS

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Abstract

The diversity of native plant species comprising of natural vegetation is closely related to patterns of soil processes controlled by environmental conditions. This study developed a logistic model integrating the relationship between spatially distributed vegetation patterns and ecological conditions of soil explicitly based along heavy metal contamination gradients. A quadrat size of 1 x 1 m was used to analyze herbaceous plant species in the vicinity of industrial area Islamabad that has been contaminated with wastewater effluents. We identified two dominant communities comprising of *Desmostachya bipinnata* and *Trifolium alexandrinum* as initial colonizers. The canonical correspondence analysis revealed that grass species were more tolerant to soil Pb concentration that ranged from 1.03 to 3.44 mg kg^{-1} soil. The analysis of rhizosphere soil samples indicated that spots that were rich in Cd concentration were mainly occupied by *Parthenium hysterophorus* along with *Malvastrum coromandelianum*. We further interpolated the spatial patterns of soil properties in which pH and organic matter contents emerged as significant indicators. In areas where topography was uneven and natural depression created sinks for soil water, relatively higher soil heavy metal concentrations were observed. The vegetation-soil interaction (e.g. root proliferation and phytoextraction potential) has influenced the ability of plants to maintain cover on contaminated sites and thus ecological conditions were modified accordingly. We therefore stress upon considering topographic aspects and native plants of an ecosystem into one continuum system to address the restoration processes on degraded lands.

Introduction

The colonization of an area with natural vegetation reflects the soil health status as well as the scale of adaptation for plant species in the prevailing environment. However, rising soil pollution problems all over the world has caused serious negative effects on plant diversity. It has been observed that heavy metals are continuously being added to soils through various agricultural and industrial activities such as the use of agrochemicals and the long-term deposition of urban sewage sludge on agricultural soils, waste disposal, waste incineration and vehicle exhausts. All these sources cause accumulation of these elements in soils and pose a threat to food safety and potential health risks. Among heavy metals, cadmium is relatively mobile in soils and is one of the most toxic. In plants, cadmium inhibits root and shoot growth, affects nutrient uptake and homeostasis, and is frequently accumulated by important crops consumed by animals and humans (Sanita di Toppi & Gabrielli, 1999). Contamination of soil with cadmium also negatively affects biodiversity and the activity of soil microbial communities (Liao *et al*., 2005). The threat of heavy metal pollution has led to an increased interest in developing systems that can remove or neutralize its toxic effects in soils, sediments and wastewaters (Mushtaq & Khan, 2010). Phytoremediation, i.e. the use of plants that have constitutive and adaptive mechanisms for tolerating or accumulating large concentrations of metals in their rhizosphere and tissues, is emerging as a potential in situ technology employed to clean up soils polluted with heavy metals (Khan *et al*., 1998; Hayes *et al*., 2003).

Currently, there are a number of reports available which describe metal-accumulating plants that are used in the removal of toxic metals from soil (Khan *et al*., 2000; Rajkumar *et al*., 2006; Safronova *et al*., 2006; Zhuang *et al*., 2007). Elevated levels of heavy metals, however, lead to impaired metabolic activity and results in reduced plant growth. The interactions between plants and beneficial rhizosphere microorganisms can enhance biomass production and tolerance of the plants to heavy metals (Rashid *et al*., 2009) rendering microorganisms an important component of phytoremediation technology (Wenzel *et al*., 1999; Glick, 2003) which is focused in this study.

Materials and Methods

Prior to initiate sampling, detailed preliminary visit was conducted to have an overview of type of vegetation present in the area. Observations regarding type of vegetation indicated that area was mostly colonized by herbaceous plants and therefore those stands were marked where natural plant species were growing. Although in first instance it appeared that density was poor but later on during vegetation sampling quite a few number of species were observed.

Vegetation data collection: After visits to the site Industrial Areas of Islamabad, soil and plant samples were collected. The vegetation sampling was conducted randomly from July 2008—February 2009. The site was visited several times during this period. Unidentified plants in the field were collected and brought to the laboratory PMAS Arid Agriculture University Rawalpindi for identification. Nomenclature of plants follows that of "Flora of Pakistan" (Nasir & Ali, 1972).

Prior to sampling, the selection of sample stands is important. For this study, two stands were selected from the industrial area for sampling. Selection of stands was based on following criteria (Cain & Castro, 1959).

- It should be large enough to contain all species belonging to the plant community.
- The habitat should be uniform within the area as far as possible.

Size of quadrat: Suitable size of quadrat is important for vegetation sampling. It is selected according to the size and spacing of the plants. Based on the visual observation of vegetation structure, the quadrat size of 1 m^2 was selected. A total of 40 quadrats in two stands of both the areas were taken. As most of the area was uncultivated so mostly vegetation was natural and where-ever this small vegetation existed, it was homogenous, that accordingly reflects that number of quadrats was sufficient.

Density: Density relates to the number of plants rooted within each quadrat. The sum of the individuals per species was calculated for the total area sampled by the small quadrats. The average density per quadrat of each species was converted to quadrat size of $1m^2$.

$$\text{Density} = \frac{\text{Number of individuals of species in all Quadrats}}{\text{Total Area Sampled}}$$

Cover: It is the percentage of quadrat area beneath the canopy of a given species (Daubenmire, 1959). Area occupied by the aerial projections of the plants in different strata was measured denoting the cover. This aspect was more visual-based and for analyzing the vegetation cover, manual approach is considered more appropriate (Cain and Castro, 1959). However, in the current study recent modifications of plant cover estimation was followed though these are actually proximate to earlier approaches (Bonham *et al*., 2004).

Cover percentage was determined as,

$$\text{Percentage Cover} = \frac{\text{Total Cover of an Individual plant}}{\text{Total Area}} \times 100$$

Vegetation analysis: The field data obtained in the form of quadrats was tabulated using Microsoft Excel® spreadsheet. Species names and their respective quadrats were arranged in such a way the species with less than 5 % occurrence were excluded. The data was analyzed when the results of environmental variables such as soil heavy metal concentrations and other related parameters were finalized. To determine the vegetation distribution pattern along soil gradients, canonical correspondence analysis (CCA) was performed. Effort was made to identify most influencing vector explaining the variations in vegetation data. Species clusters with maximum grouping were plotted using biplot ordination technique (Ter Braak, 1995). Generalized liner model was applied to plant species with highest density for generating contours trends and responsiveness towards positive and negative zones. MultiVariate Statistical Package MVSP 3.1 for Windows was used for vegetation analysis.

Soil sampling and plant collection: Corresponding to quadrats, which were taken from each site (20 quadrats from each stand) rhizosphere soil samples were also taken. In this way, within each quadrat soil from the root zone area was collected and brought to the laboratory. A total of 40 samples were collected from both the stands and then air dried prior to sieve through 2 mm mesh. Composite soil samples were prepared by mixing the five quadrat samples of closest vicinity and used for analyzing different parameters.

Statistical analysis: Comparison between the sites for metal uptake by *Trifolium alexandrinum* was done using one way ANOVA. Mean and standard deviation values were calculated which were used to represent bar charts. Binary logistic regression was performed to predict the heavy metals (Cd and Pb) concentration in soil for which five categorical covariates (plant density, plant cover, soil moisture, topography and distance from wastewater channel) were used as independent variables. Plant cover and topography were binary coded with good cover and even topography used as reference categories. For other three independent variables, high plant density, extremely moist soil and very far from wastewater channel were used as reference categories. The data was statistically analyzed using SPSS version 13 for Windows.

Results and Discussion

Majority of the species observed in the study area were representing patchy colonization. Somehow the dominant colonizers were herbaceous vegetation with more or less same cover. However, the density of the species seems to be the indicator of plants' response to existing soil contamination pressure. General soil characteristics of the sites indicate that Cd and Pb concentrations range between 0.75 to 1.8 mg kg^{-1} and 1.03 to 3.44 mg kg^{-1} respectively (Table 1). Based on a skewness indicator range between –1 and 1, all the soil parameters fell into normal distributions except soil moisture which was considered non–normal or skewed.

Table 1. Edaphic characteristics and heavy metal concentration in field soil samples (n = 25).

Soil parameters	Mean	Minimum	Maximum	St.dev	Skewness	Kurtosis
pH	7.82	7.20	8.40	0.33	–0.15	0.94
OM (%)	1.91	1.40	2.30	0.28	–0.52	–0.23
Moisture (%)	4.55	1.28	11.50	2.82	1.74	4.04
Cd (mg kg^{-1})	1.23	0.75	1.80	0.34	0.01	–0.60
Pb (mg kg^{-1})	2.32	1.03	3.44	0.80	–0.42	–1.01
Clay (%)	9.09	8.10	10.00	0.65	–0.19	–1.22
P (ppm)	0.81	0.29	1.40	0.43	–0.04	–1.89
K (ppm)	21.48	14.60	30.40	5.17	0.31	–0.94

Results of logistic regression are presented in Tables 2 and 3 which shows that increase in soil moisture contents has lead to increase Pb in soil significantly ($p<0.05$). Among other soil parameters, uneven topography appeared to be significantly associated for increased soil Pb values and for every one degree change from even to uneven land surface, the soil Pb contents rise with a factor of 5.3 indicating a direct relationship between topographic feature and soil Pb contamination (Table 2). Spots near the wastewater drain and reduced plant cover were also significant with rising Pb contents in soil. Predictive analysis for soil Cd using logistic regression revealed that plant cover, topography and distance from the wastewater drain have significant relation with soil Cd contamination (Table 3). Plant cover became scarce with rising soil Cd level while sites where topography was uneven has significantly higher Cd concentration as compared to sites with even topography. Distance from wastewater channel was also significant in making soil contaminated with Cd and odds ratio 'Exp(B)' showed that odds of soil Cd concentration rise with a factor of 6.73 when we move from far away spots to areas near the wastewater channels (Table 3).

Table 2. Logistic regression analysis for the prediction of soil Pb concentration in industrial effluent contaminated area.

Pb concentration in soil	B	S.E.	df	P-value	Exp(B)
Moist soil	1.473	0.715	1	0.039	4.362
Dry soil	1.184	0.788	1	0.133	3.267
Poor plant density	0.955	0.829	1	0.249	2.599
Moderate plant density	–0.541	0.768	1	0.481	0.582
Topography (uneven)	1.673	0.601	1	0.005	5.329
Area (near wastewater drain)	0.490	0.690	1	0.477	1.633
Area (far from water drain)	1.516	0.687	1	0.027	4.556
Plant cover (scarce)	1.179	0.589	1	0.045	0.308
Constant	–1.355	0.782	1	0.083	0.258

Table 3. Logistic regression analysis for the prediction of soil Cd concentration in industrial effluent contaminated area.

Cd concentration in soil	B	S.E.	df	P-value	Exp(B)
Moist soil	–0.207	0.609	1	0.734	0.813
Dry soil	–0.445	0.707	1	0.528	0.641
Poor plant density	–0.289	0.777	1	0.710	0.749
Moderate plant density	–1.209	0.797	1	0.129	0.298
Topography (uneven)	1.357	0.512	1	0.008	3.884
Area (near wastewater drain)	1.907	0.660	1	0.004	6.735
Area (far from water drain)	1.165	0.643	1	0.070	3.205
Plant cover (scarce)	1.788	0.540	1	0.001	5.979
Constant	–2.302	0.970	1	0.018	0.100

Canonical correspondence analysis (CCA) performed to identify distribution patterns along heavy metal concentration gradient revealed contrasting variations among species tolerance against soil Cd and Pb contamination. Ordination diagram have shown spots rich in Cd concentration were mainly occupied by *Parthenium hysterophorus* along with *Malvastrum coromandelianum* and *Trifolium alexandrinum* (Fig. 1). However, soil with spiked Pb contents had *Desmostachya bipinnata* colonization with some patchy occurrence of *Trifolium alexandrinum*. The former plant species has inherent feature to withstand soil Pb toxicity while latter specie seems to have better adaptive mechanism to grown of metal contaminated soil. Probably this was the reason *T. alexandrinum* was found growing in both Cd as well as Pb spiked spots. Inference drawn here is based on soil features which is considered a promising way to describe phytosocialogical trends (Ali *et al*., 2004). We therefore infer from CCA that distribution pattern of plant species along metal concentration gradient has definite relation. The eigenvalues of first two canonical axes accounts 71 % of the variation in our data set (Table 4) which on one hand indicates significant correlation between species-environment and on the other it shows that edaphic characteristics of site industrial area Islamabad were the main factors contributing in the origin of different vegetation patterns. The regression model applied to the distribution of *Trifolium alexandrinum* was Generalized Linear Model (GLM) which is represented in contour plots (Fig. 2). The model suggests that first canonical axis has strong relation with contours 1.8 to 3.4 and along these locations most of the *Trifolium alexandrinum* density was observed. Therefore, it is seems plausible to identify soil heavy metals as an environmental gradient along which the dominant species has colonized. Generalized linear modelling has also been used to describe the response of more than one species along environmental variables (Odland, 1997) however the present work requires identifying most colonizing species in contaminated areas therefore only one species was included in this model. Here the GLM indicates that most of contours originate along first half of the canonical axis with higher values converging towards positive zones.

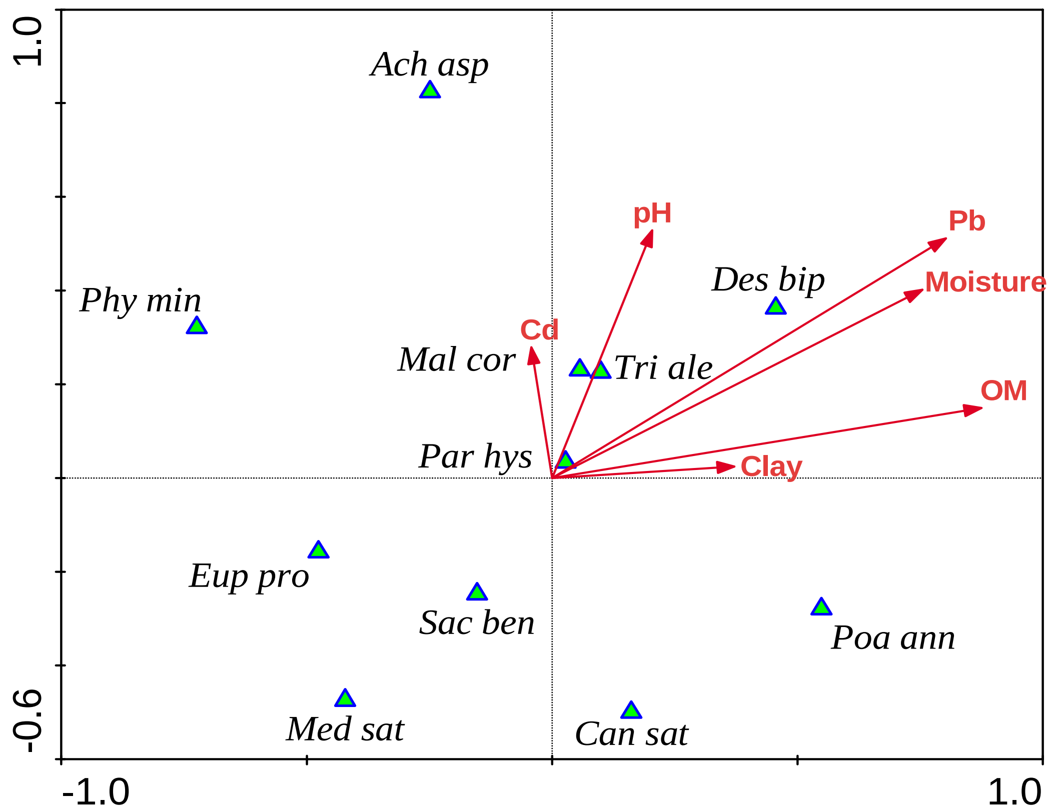

Fig. 1. Canonical correspondence analysis for the species and environmental variables. Abbreviations of the plants are as follows: Acy asp = *Achyranthes aspera*, Can sat = *Cannabis sativa*, Eup pro = *Euphorbia prostrata*, Des bip = *Desmostachya bipinnata*, Mal cor = *Malvastrum coromandelianum*, Med sat = *Medicago sativa*, Phy min = *Physalis minima*, Poa ann = *Poa annua*, Par hys = *Parthenium hysterophorus*, Sac ben = *Saccharum bengalense*, Tri ale = *Trifolium alexandrinum*.

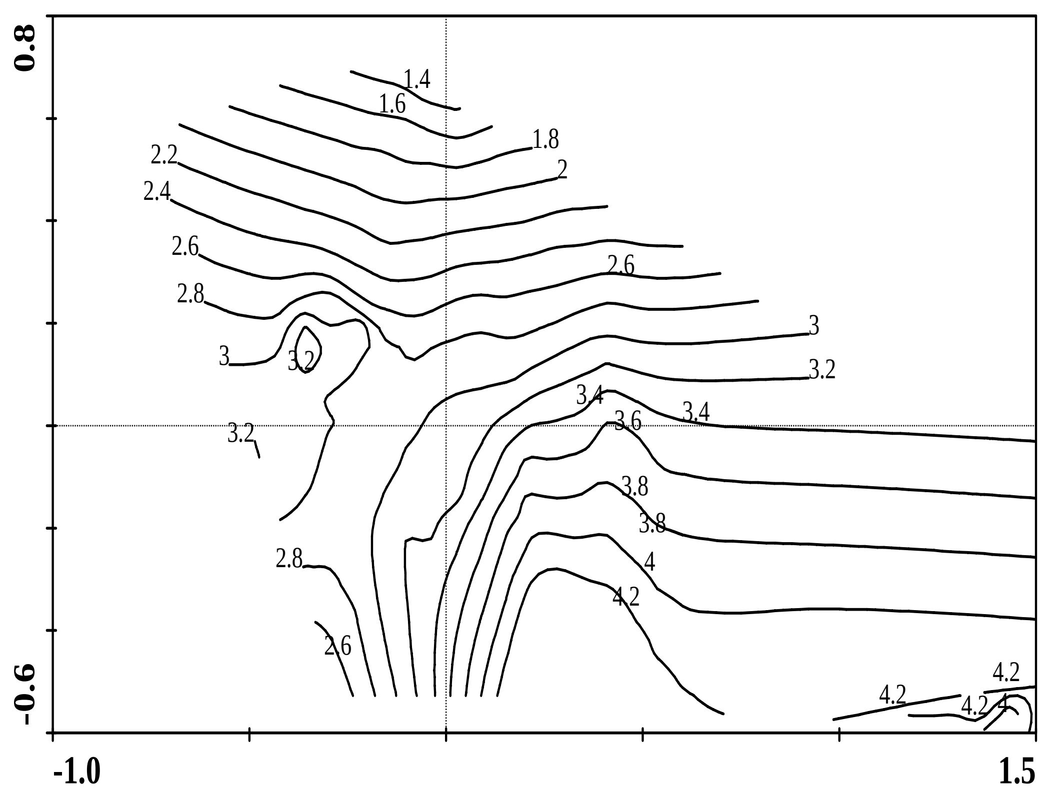

Fig. 2. GLM contouring for *Trifolium alexandrinum* along canonical axes.

Table 4. Eigenvalues for all canonical axes under reduced model performed for canonical correspondence analysis.

Summary of canonical analysis for industrial area Islamabad	Axes				Total inertia
	1	2	3	4	
Eigenvalues	0.127	0.101	0.063	0.015	1.429
Species-environment correlations	0.728	0.714	0.432	0.307	
Cumulative percentage variance					
of species data	8.9	16.0	20.4	21.5	
of species-environment relation	39.9	71.6	91.5	96.3	
Sum of all eigenvalues					1.429
Sum of all canonical eigenvalues					0.319

The uptake of Pb among four most frequently observed plant species has same trend with root Pb concentration higher than shoot (Fig. 3). However, the difference between root and shoot Pb contents was significant for *D. bipinnata* and *T. alexandrinum*. On the other hand, Cd uptake from soil and its subsequent accumulation in plant tissues was different among four species collected from the field. A significantly higher root Cd concentration than shoot was observed in *P. hysterophorus* and *M. coromandelianum* while difference between root and shoot Cd values were non significant in *D. bipinnata* and *T. alexandrinum* (Fig. 3). Since these four plant species were present in greater density therefore, they were analyzed for tissue metal accumulation. Significantly higher amount of Cd and Pb found only in root tissues in all four species indicates that these plants are phytostabilizers and probably this was the reason that a higher plant density for these species was observed. Previously, from this area, 3.69 mg kg^{-1} was detected as maximum Pb in tree species (Pirzada *et al*., 2009) however, we found almost similar range of Pb in root tissues of a grass specie (*D. bipinnata*) as maximum amount. Our result therefore, point outs that herbaceous flora especially grass species can best be utilized as initial colonizers where industrial effluents rendered the soils unsuitable for plant growth.

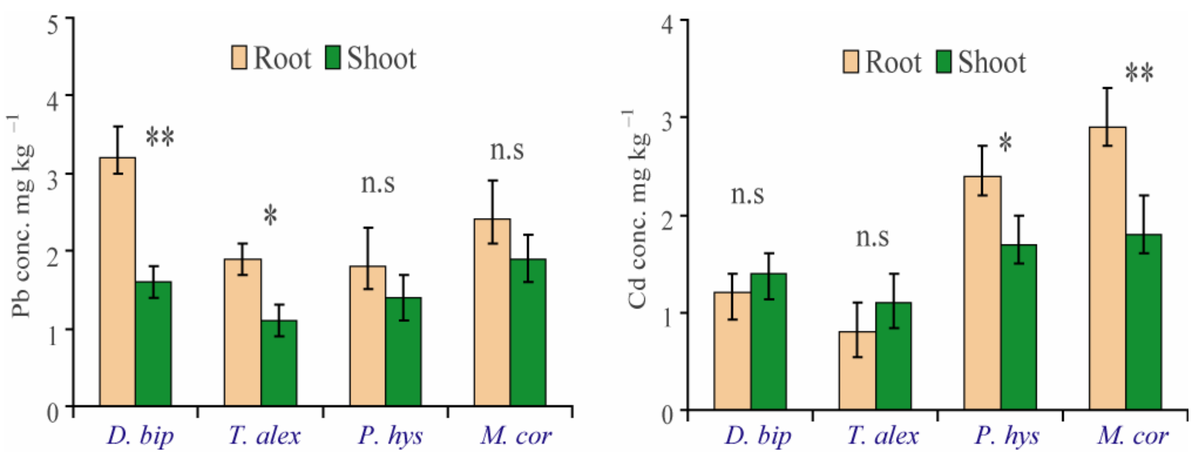

Fig. 3. Comparison of root and shoot heavy metal concentrations among different plant species. Bar charts showing mean values and standard deviations for Cd and Pb in plant tissues (n=6). D. bip = *Desmostachya bipinnata*, T. alex = *Trifolium alexandrinum*, P. hys = *Parthenium hysterophorus*, M. cor = *Malvastrum coromandelianum*.
* p<0.05; ** p< 0.01; n.s = non significant

Conclusions

The study gives considerable evidence that edaphic characteristic of industrially polluted areas governs the vegetation types that prevail in the wake of heavy metal tolerance. Although we observed that plant species tend of differ in responding to soil metal toxicity yet texture, moisture and pH values has strong influence in enhancing the plant's capability to withstand contamination pressure. Moreover, phytoaccumulation of metals is largely a function of inherent ability of plant species however, if they are adapted to prevailing environmental conditions such as *Desmostachya bipinnata* and *Trifolium alexandrinum*, as indicated in our study, then these species can be used to restore degraded lands.

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