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Effects of mining-associated lead and zinc soil contamination on native floristic quality

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ABSTRACT

We assessed the quality of plant communities across a range of lead (Pb) and zinc (Zn) soil concentrations at a variety of sites associated with Pb mining in southeast Missouri, USA. In a novel application, two standard floristic quality measures, Mean Coefficient of Conservatism (Mean C) and Floristic Quality Index (FQI), were examined in relation to concentrations of Pb and Zn, soil nutrients, and other soil characteristics. Nonmetric Multidimensional Scaling and Regression Tree Analyses identified soil Pb and Zn concentrations as primary explanatory variables for plant community composition and indicated negative relationships between soil metals concentrations and both Mean C and FQI. Univariate regression also demonstrated significant negative relationships between metals concentrations and floristic quality. The negative effects of metals in native soils with otherwise relatively undisturbed conditions indicate that elevated soil metals concentrations adversely affect native floristic quality where no other human disturbance is evident.

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1. Introduction

We investigated associations between soil concentrations of lead (Pb) and zinc (Zn) and the floristic quality of otherwise relatively undisturbed plant communities adjacent to mine waste and a Pb smelter in the Southeast Missouri Mining District (SEMO), Missouri, USA (Fig. 1). Sites adjacent to Pb smelters and mine waste disposal sites are known to contain elevated soil metals concentrations (Kabata-Pendias and Pendias, 1992), and phytotoxic effects of metals contamination have been demonstrated in both field and laboratory experiments (Andersson, 1988; Das et al., 1997; Fargasova, 2001; Kabata-Pendias and Pendias, 1992; Pahlsson, 1989). Specifically, Pb inhibits plant growth and the activity of enzymes required for photosynthesis, interferes with cell division and respiration, reduces water absorption and transpiration, and reduces chlorophyll, carotenoid, and adenosine triphosphate (ATP) synthesis (Fargasova, 2001; Kabata-Pendias and Pendias, 1992). Although Zn is an essential micronutrient for plants, activity of enzymes involved in photosynthesis and hydrolysis can decrease in plants watered with solution concentrations as low as 650 μg/L Zn; solutions with Zn concentrations of 100–200 μg/L can disturb mitotic activity in root tips (Pahlsson, 1989).

A review by Fletcher et al., in 1988 showed that most phytotoxicity research has focused on agricultural species, and the sensitivity of most native plants to Pb and Zn was unknown. Little has changed in the intervening years; a *post-priori* search of the ECOTOX database (U.S. Environmental Protection Agency, 2009) using the 439 plant species found during this study yielded only seven studies examining the phytotoxic effects of either Zn or Pb. A handful of studies have documented negative community-level effects on native flora resulting from metals contamination related to mining activity (Beyer et al., 2011; Clark and Clark, 1981; LeJeune et al., 1996; Pierzynski and Fick, 2007; Thompson and Proctor, 1983), but only one (Kindscher et al., 2008) has used the particular measures of floristic quality described in this paper. Here, we use Floristic Quality Assessment (Swink and Wilhelm, 1994) to examine the effects of Pb and Zn contamination on the floristic quality of native plant communities. This approach is based on the premise that native plant species differ in sensitivity to disturbance and that the ecological integrity of a site is reflected by the suite of native species that occur there. Although not all locations have the necessary information to apply Floristic Quality Assessment (FQA) at present, other community-level metrics can be investigated in settings where FQA information is not yet available.

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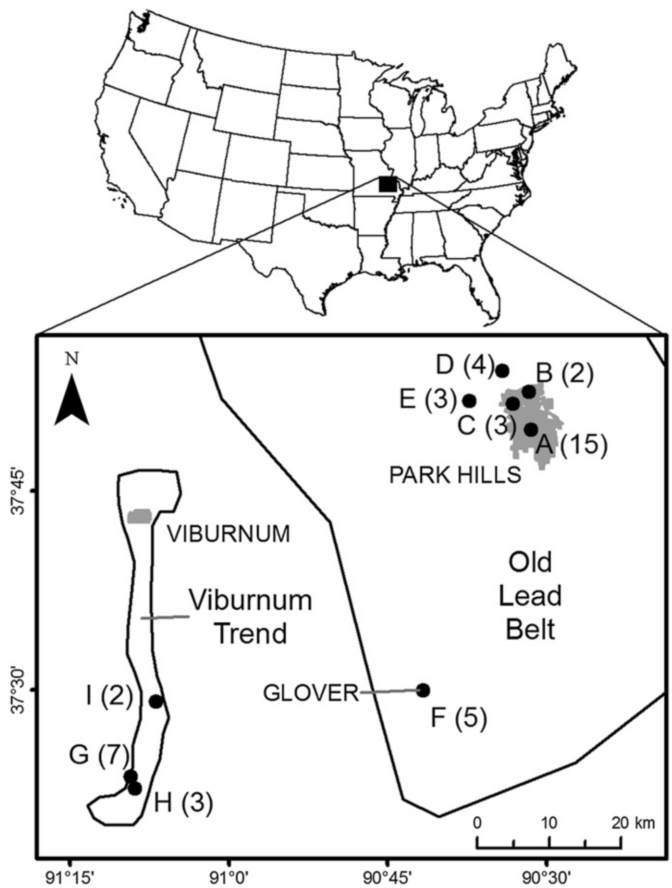

Fig. 1. Plant community sampling sites and towns (shaded areas) within subregions of the Southeast Missouri Mining District, Missouri, USA (numbers within parentheses indicate the number of plots at each site).

2. Materials and methods

2.1. Study area

In the Southeast Missouri Mining District, Pb has been mined in two subregions known as the Old Lead Belt and the Viburnum Trend (Fig. 1). Large-scale mines operated in the Old Lead Belt for more than a century until the 1970s, at which time mining shifted to the Viburnum Trend where it continues to the present day (U.S. Fish and Wildlife Service and Missouri Department of Natural Resources, 2008). The lead smelter at Glover operated from 1968 to 2003, at which time the facility was placed in a non-functional "care and maintenance" status (The Doe Run Company, 2003). Waste from the mining operations include piles of chat (a coarse-grained by-product of outdated physical-separation processes) and impoundments of tailings (a fine-grained by-product of modern chemical-separation processes), which contain millions of cubic meters of mine waste with Pb and Zn concentrations as high as 17,000 and 25,000 mg/kg (NewFields, Inc., 2006). These are sources of terrestrial and aquatic contamination via seepage and erosion (Besser et al., 2009). Background levels of Pb and Zn within the mining regions are 62 and 71 mg/kg respectively (NewFields, Inc., 2006); concentrations adjacent to mine waste are much higher than background levels and can exceed 10,000 mg/kg for Pb and 2300 mg/kg for Zn (U.S. Environmental Protection Agency, 2006). Contamination from these sites has contributed to the loss of biota, including mussels and crayfish, from aquatic systems (Schmitt et al., 2007).

Presettlement vegetation across the region was a mixture of forests and woodlands dominated by oak and pine, with inclusions of dolomite and igneous glade complexes; present-day vegetation is dominated by second-growth oak and pine-oak forests and woodlands, with lesser amounts of pasture in valley bottoms and on moderate slopes (Nigh and Schroeder, 2002). Effects of metals contamination on terrestrial vegetation in the region had not been documented prior to the initiation of this study.

2.2. Data collection

2.2.1. Plot selection

Within the study areas, we identified 8 sampling sites adjacent to mine waste and 1 site adjacent to the smelter at Glover, Missouri (Fig. 1). These sites were all on native soils with no evidence of chat, tailings or other obvious deposits of mine waste. We selected sites with relatively undisturbed second-growth oak and pine-oak forests and woodlands and their associated suite of ground flora species (Nigh and Schroeder, 2002). Sites were considered relatively undisturbed if existing vegetation indicated no evidence of logging, grazing, or other human disturbance. Evidence of logging included remnant stumps or skidder trails. Evidence of grazing included persistent animal tracks attributable to domestic livestock or dominance by plant species commonly used in pasture mixes, particularly tall fescue (*Schedonorus phoenix* (Scop.) Holub). Other evidence of human activity included roads or all-terrain vehicle trails, utility right-of-ways, or evidence of soil grading.

Within sites meeting these criteria, several potential plot locations were randomly generated using geographic information system software from which one was randomly selected for sampling. Plots measured 20 m $\times$ 20 m (400 m^2), with edges laid out in cardinal directions. If necessary, plots were reoriented and reshaped (retaining the 400 m^2 search area) in order to remain within the dominant plant community type. We recorded the location of the southwest corner of each plot using a handheld global positioning system (GPS) receiver, and each plot was photographed from the GPS point toward the opposing corner. We sampled 44 plots in 9 sites; 27 plots at five sites in the Old Lead Belt, 12 plots three sites in the Viburnum Trend, and 5 plots in one site adjacent to the Pb smelter at Glover (Fig. 1). Sampling began in early June 2008 and concluded in early September 2008.

2.2.2. Plant community sampling

Plant communities were sampled in three strata: the canopy and subcanopy layer (woody species taller than 5 m), the shrub and sapling layer (woody species between 1 and 5 m tall), and the ground flora layer (herbaceous flora and woody stems providing foliar cover under 1 m). Within each stratum, we identified each species present and estimated to the nearest one percent its foliar cover within the entire 400 m^2 plot (Daubenmire, 1959). Nomenclature followed the USDA PLANTS database (U.S. Department of Agriculture, Natural Resource Conservation Service, 2008). The primary references for plant identification were *Flora of Missouri* (Steyermark, 1963), and *Steyermark's Flora of Missouri Volume 1* (Yatskievych, 1999) and *Volume 2* (Yatskievych, 2006). Plants that were difficult to identify in the field were collected for identification purposes and compared against reference specimens in both the USGS Columbia Environmental Research Center herbarium and the Missouri Botanical Garden reference collection for the Flora of Missouri Project. Identifications of most collected specimens were confirmed with the author of the revised *Flora of Missouri* (G. Yatskievych, personal communication).

2.2.3. Soil sampling

We collected topsoil (0–20 cm) and subsoil (20–35 cm) from three small pits in two opposing corners and in the approximate center of each plot. Following guidelines for sampling residential soils for metal contamination (U.S. Environmental Protection Agency, 2000, 2003), we used a tempered steel shovel to dig a hole, then cleaned the exposed soil surfaces with a plastic scoop to reveal soils that had not come in contact with the steel shovel. A clean plastic scoop was used to excavate laterally into the sides of the hole and remove samples. Sampling scoops were cleaned with a plastic brush and deionized water between collection events. All topsoil samples and all subsoil samples from the three pits in each plot were combined in labeled plastic zippered bags and stored at ambient temperature until laboratory analyses could be performed. Metals concentrations were measured in the Missouri Department of Natural Resources Environmental Service Program laboratory using handheld X-ray Fluorometer (XRF) standard operating procedures (Missouri Department of Natural Resources, 2008). Soil samples were also analyzed at the University of Missouri soil testing laboratory for organic matter, extractable phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), pH in salt solution (pH), neutralizable acidity (NA), and cation exchange capacity (CEC) using standard soil testing procedures described in Nathan et al. (2007).

2.3. Data analysis

2.3.1. Floristic quality measures

The primary dependent variables used in our analyses, Mean C and Floristic Quality Index (FQI), were calculated using Floristic Quality Assessment methods (Swink and Wilhelm, 1994). Expert panels assign each native species in a geographic region a Coefficient of Conservatism (C) from 0 to 10, based on its tolerance of human disturbance and its affinity for natural plant communities.

Table 1
Concentrations of metals, concentrations of nutrients, pH, neutralizable acidity (NA), percent organic matter, and cation exchange capacity (CEC) for soils in plant community plots in the Southeast Missouri Mining District, Missouri, USA.

Site-plot	Pb (mg/kg)		Zn (mg/kg)		P (kg/hectare)		Ca (kg/hectare)		Mg (kg/hectare)		K (kg/hectare)		pH		NA (meq/100 g)		% organic matter		CEC (meq/100 g)	
	Top[a]	Sub[b]	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub
A-1	41.2	30.8	7.8	6.7	427.8	393.1	76.2	259.8	145.6	160.2	29.2	38.3	3.9	4.	8.0	10.0	1.7	1.6	9.4	12.0
A-2	157.1	149.9	5.6	3.4	1768.5	1919.7	489.4	597.0	163.5	145.6	109.4	105	4.8	5.2	6.0	4.0	2.9	2.1	12.0	10.7
A-3	50.2	43.6	11.2	6.7	293.4	405.4	103.0	269.9	124.3	124.3	49.4	63.7	3.9	3.9	6.5	7.5	1.3	0.7	7.7	9.6
A-4	53.5	39.4	10.1	20.2	266.6	319.2	112.0	174.7	112.0	127.7	42.0	33.4	3.9	3.9	7.0	9.0	1.5	1.0	8.1	10.5
A-5	105.3	102.3	13.4	10.1	2069.8	1509.8	347.2	353.9	201.6	161.3	88.0	89.5	5.7	5.5	2.0	2.5	2.4	1.4	8.1	7.4
A-6	139.9	112.8	17.9	7.8	2796.6	2096.6	600.3	502.9	245.3	149.0	109.8	96.5	5.4	5.4	5.5	3.5	3.9	2.2	14.3	10.2
A-7	554.9	221.8	3.4	3.4	2786.6	1859.2	597.0	519.7	155.7	134.4	123.1	81.2	7.2	7.0	0.0	0.0	2.5	1.3	8.6	6.2
A-8	405.2	120.8	3.4	1.1	3591.8	2909.8	1095.4	1221.9	199.4	226.2	70.4	34.6	7.5	7.0	0.0	0.0	2.4	1.6	12.3	11.3
A-9	272.0	133.8	3.4	1.1	2604.0	1348.5	517.4	452.5	124.3	118.7	88.8	70.3	7.3	6.8	0.0	0.0	1.9	0.9	7.9	4.8
A-10	178.0	50.3	4.5	2.2	2261.3	1830.1	623.8	657.4	152.3	127.7	62.3	45.3	7.1	6.9	0.0	0.0	1.9	0.9	7.5	6.7
A-11	212.7	93.3	7.8	6.7	3233.4	2381.1	779.5	620.5	206.1	180.3	98.0	78.7	7.1	6.9	0.0	0.0	2.8	1.7	10.4	7.8
A-12	334.7	134.7	6.7	3.4	3048.6	1895.0	757.1	520.8	160.2	122.1	134.0	102	7.1	7.0	0.0	0.0	2.9	1.4	9.8	6.3
A-13	244.3	69.7	6.7	5.6	3400.3	1534.4	721.3	385.3	189.3	155.7	104.7	73	7.2	7.0	0.0	0.0	3.2	1.1	10.5	5.0
A-14	190.3	38.3	4.5	1.1	2721.6	2094.4	905.0	1141.3	226.2	216.2	58.7	38	6.9	6.6	0.0	0.5	2.1	0.8	9.7	9.7
A-15	176.7	75.3	4.5	3.4	2832.5	2347.5	1135.7	1288.0	238.6	226.2	53.7	39	6.1	5.9	2.0	2.0	3.2	1.7	12.8	12.3
B-1	3249.3	3679.3	16.8	0.0	2590.6	0.0	516.3	0.0	168.0	0.0	849.7	852	7.1	ND	0.0	ND	2.3	ND	7.9	ND
B-2	1768.7	2721.0	14.6	12.3	2418.1	991.2	413.3	218.4	131.0	109.8	615.7	638.3	7.2	7.1	0.0	0.0	2.1	1.1	7.1	3.2
C-1	802.3	110.0	2.2	2.2	6620.3	3476.5	1298.1	1274.6	133.3	135.5	1155.7	123.7	7.4	7.3	0.0	0.0	3.5	3.4	19.8	12.7
C-2	963.3	130.8	10.1	2.2	4132.8	2011.5	1068.5	731.4	172.5	128.8	1135.7	129.6	7.2	7.0	0.0	0.0	6.4	2.5	13.4	7.4
C-3	724.3	134.7	7.8	3.4	3539.2	1155.8	798.6	325.9	114.2	108.6	769.3	182.7	7.2	7.0	0.0	0.0	5.4	1.5	11.0	3.9
D–1	931.0	1202.5	19.0	15.7	2694.7	1721.4	674.2	469.3	154.6	142.2	1171.9	1276.1	7.2	7.3	0.0	0.0	1.7	1.1	8.7	5.8
D-2	100.7	58.3	7.8	4.5	2483.0	2381.1	816.5	1034.9	188.2	207.2	55.4	46.8	7.0	6.8	0.0	0.5	2.4	1.5	8.8	9.9
D-3	407.6	192.3	4.5	4.5	6273.1	4972.8	2072.0	1700.2	211.7	183.7	219.3	108.9	7.2	7.3	0.0	0.0	7.1	4.8	22.0	17.6
D-4	940.4	1219.8	28.0	16.8	5103.8	2613.0	972.2	579.0	247.5	174.7	698.5	634.6	7.0	7.3	0.0	0.0	6.1	1.2	15.3	8.2
E–1	57.3	34.3	7.8	2.2	1433.6	1377.6	779.5	1186.1	200.5	268.8	35.7	38.3	5.0	4.7	4.5	5.5	2.6	2.0	10.8	13.3
E–2	89.7	37.7	4.5	3.4	2615.2	2035.0	861.3	1009.1	154.6	163.5	119.3	97.7	7.0	6.8	0.0	0.0	2.8	1.5	9.2	8.5
E–3	98.9	55	2.2	1.1	3259.2	2573.8	1167.0	1218.6	194.9	222.9	100.1	112.3	7.0	ND	0.0	ND	3.3	2.4	11.8	10.5
F-1	377.7	157.3	0.0	9.0	0.0	1032.6	0.0	76.2	0.0	160.2	67.3	66.7	ND	4.1	ND	7.0	ND	2.1	ND	9.8
F-2	472.0	157.7	3.4	5.6	1877.1	1543.4	525.3	440.2	151.2	118.7	85.0	70.3	5.8	5.5	1.5	2.0	3.5	2.0	7.8	7.2
F-3	478.0	84.3	7.8	5.6	2915.4	2037.3	800.8	701.1	398.7	333.8	105.0	70.3	7.2	7.3	0.0	0.0	5.1	2.1	9.9	7.5
F-4	696.0	98.3	4.5	4.5	6513.9	5055.7	2268.0	2147.0	350.6	358.4	135.7	121	7.0	ND	0.0	ND	10.1	6.2	23.4	19.7
F-5	1413.0	123.7	15.7	12.3	192.6	48.2	106.4	48.2	169.1	140.0	225.0	169.3	4.4	4.2	9.0	7.0	5.5	3.0	10.0	7.4
G-1	32.0	15.8	12.3	6.7	722.4	341.6	212.8	165.8	174.7	125.4	27.2	27	4.4	4.4	9.0	6.0	3.8	1.6	11.6	7.5
G-2	34.0	20.0	6.7	4.5	276.6	246.4	82.9	132.2	146.7	131.0	24.8	27.9	3.9	4.3	10.5	6.5	3.1	1.2	11.6	7.7
G-3	40.2	17.2	16.8	7.8	502.9	340.5	100.8	98.6	137.8	106.4	27.6	24	3.8	4.0	14.0	8.5	4.6	1.3	15.7	9.7
G-4	33.2	12.2	10.1	10.1	312.5	250.9	117.6	121.0	133.3	100.8	28.9	20.9	4.0	4.5	9.5	4.5	2.8	1.0	10.8	5.6
G-5	57.7	12.5	13.4	14.6	605.9	302.4	266.6	166.9	138.9	90.7	36.2	21.5	4.0	4.4	14.5	6.0	5.4	1.6	17.0	7.4
G-6	30.0	20	0.0	3.4	203.8	80.6	101.9	163.5	105.3	106.4	26.0	22.7	ND	4.2	ND	4.5	2.9	1.0	1.0	5.4
G-7	24.3	43.3	9.0	0.0	1461.6	0.0	413.3	0.0	154.6	0.0	24.7	36.7	5.2	ND	5.0	ND	5.7	ND	10.0	ND
H-1	97.3	19.7	15.7	9.0	2814.6	980.0	717.9	312.5	131.0	93.0	98.7	31.3	7.2	6.6	0.0	0.5	3.4	1.1	9.1	4.0
H-2	88.0	22.7	5.6	4.5	3156.2	817.6	1006.9	463.7	97.4	79.5	67.0	27.3	6.9	6.2	0.0	0.5	3.8	1.4	10.9	4.1
H-3	236.0	35.7	7.8	5.6	3921.1	1703.5	941.9	534.2	114.2	116.5	249.7	41.7	7.2	6.6	0.0	0.5	4.6	2.5	12.4	6.4
I-1	35.8	17.7	2.2	6.7	901.6	651.8	152.3	482.7	45.9	153.4	46.1	41.0	7.7	6.1	0.0	1.0	0.4	1.9	2.6	4.4
I-2	93.7	29.7	11.2	11.2	3645.6	2657.8	954.2	818.7	281.1	216.2	126.3	86.3	7.0	7.0	0.0	0.0	3.5	2.5	12.0	9.2

ND = no data.
[a] Topsoil.
[b] Subsoil.

Species with low C values (0–3) tend to be generalists that occur throughout the landscape in disturbed and undisturbed habitats. Species with high C values (8–10) require systems undisturbed by humans where natural processes to which that species has evolved are functioning. We used C values for Missouri flora reported in Ladd (1993).

Mean C is the arithmetic mean C value of all native species occurring in a sampling unit; values above 4.5 indicate sites in which ecological processes that shape and define a given habitat are functioning (Swink and Wilhelm, 1994). The FQI is the product of Mean C and the square root of the native species richness; noteworthy remnants of natural communities frequently have FQI values above 45 (Swink and Wilhelm, 1994). Both Mean C and FQI are unitless.

Non-native species typically are excluded from Floristic Quality Assessments. Therefore, in order to quantify floristic quality changes in native plant communities reflected by the presence of exotic (non-native) species, we also calculated exotic species richness and percent exotic species foliar cover, and the ratios of these values to those of native species in each plot.

2.3.2. Nonmetric Multidimensional Scaling ordination

Nonmetric Multidimensional Scaling (NMS) was used to understand and display differences in plant community composition among plots and to identify environmental factors correlated with those differences. Each species record was first converted to a stratum-specific record by appending a stratum code as a prefix to the species code; for example, *Acer rubrum* (acru) in the ground flora (g) became “g-acru”. This data-conversion technique retained all of the information concerning plot-specific vegetation structure and allowed for simultaneous analysis of data from multiple vegetation strata. Cover values were then log-transformed and analyzed using the Sorensen (Bray–Curtis) distance measure and the “Slow and Thorough” autopilot setting in PC-ORD v. 6.0 (McCune and Mefford, 1999). Correlation scores and joint plots were used to examine the relationships

Table 2
Floristic quality measures for plant community plots in the Southeast Missouri Mining District, Missouri, USA.

Site-plot	Species richness			Total combined foliar cover (%)			Floristic Quality Assessment	
	Exotic	Native	Exotic: Native	Exotic	Native	Exotic: Native	Mean C[a]	FQI[b]
A-1	0	50	0.00	0	183	0.00	4.82	34.08
A-2	0	132	0.00	0	210	0.00	4.30	49.35
A-3	0	50	0.00	0	122	0.00	4.48	31.68
A-4	0	66	0.00	0	110	0.00	4.47	36.31
A-5	1	105	0.01	1	206	0.00	3.93	40.30
A-6	3	102	0.03	3	216	0.01	4.02	40.60
A-7	2	83	0.02	3	154	0.02	4.39	39.95
A-8	1	98	0.01	1	190	0.01	4.29	42.43
A-9	0	77	0.00	0	185	0.00	4.55	39.89
A-10	1	69	0.01	1	157	0.01	4.29	35.63
A-11	1	47	0.02	1	139	0.01	4.47	30.63
A-12	1	67	0.01	1	175	0.01	4.52	37.02
A-13	1	67	0.01	1	191	0.01	4.54	37.14
A-14	0	70	0.00	0	186	0.00	4.29	35.86
A-15	0	74	0.00	0	168	0.00	4.19	36.04
B-1	9	59	0.15	98	175	0.56	3.63	27.86
B-2	4	69	0.06	7	231	0.03	3.30	27.45
C-1	3	63	0.05	3	157	0.02	4.40	34.90
C-2	0	58	0.00	0	226	0.00	3.98	30.33
C-3	1	58	0.02	1	188	0.01	4.41	33.61
D-1	6	74	0.08	12	243	0.05	3.43	29.53
D-2	0	77	0.00	0	196	0.00	4.35	38.18
D-3	0	136	0.00	0	232	0.00	4.52	52.74
D-4	4	44	0.09	4	260	0.02	3.41	22.61
E–1	2	55	0.04	4	170	0.02	4.24	31.42
E–2	0	63	0.00	0	249	0.00	4.10	32.50
E–3	0	81	0.00	0	224	0.00	4.22	38.00
F-1	0	79	0.00	0	195	0.00	4.78	42.53
F-2	1	107	0.01	1	244	0.00	4.31	44.57
F-3	0	84	0.00	0	255	0.00	4.42	40.48
F-4	0	77	0.00	0	203	0.00	4.19	36.81
F-5	0	61	0.00	0	175	0.00	4.80	37.51
G-1	3	96	0.03	3	267	0.01	4.44	43.48
G-2	0	58	0.00	0	193	0.00	4.78	36.37
G-3	0	83	0.00	0	261	0.00	4.75	43.25
G-4	0	53	0.00	0	205	0.00	4.64	33.79
G-5	0	100	0.00	0	369	0.00	4.64	46.40
G-6	0	66	0.00	0	234	0.00	4.62	37.54
G-7	0	80	0.00	0	235	0.00	4.80	42.93
H-1	1	81	0.01	1	216	0.00	4.57	41.11
H-2	0	76	0.00	0	222	0.00	4.61	40.15
H-3	1	68	0.01	1	262	0.00	4.69	38.68
I-1	0	68	0.00	0	170	0.00	4.59	37.84
I-2	0	78	0.00	0	255	0.00	4.87	43.03

[a] Coefficient of Conservatism.
[b] Floristic Quality Index = (Mean C) × (native richness)$^{1/2}$.

between all floristic quality measures and all available soil variables.

2.3.3. Regression tree analysis

We used least-squares regression trees to explore which soil variables best explain variation in Mean C and FQI (SYSTAT v. 11; Systat Software, Inc., 2004). Regression tree models use non-parametric, recursive methods to partition datasets into increasingly homogeneous subgroups with respect to the response variable (Breiman et al., 1984). Regression trees are appropriate for determining which environmental variables explain differences in species composition or community metrics; as recursive models, they can capture relationships that are difficult to reconcile with conventional univariate or multivariate linear models (Urban, 2002). Regression trees included Pb and Zn concentrations for subsoil, topsoil and the topsoil/subsoil mean concentration, as well as all nutrients and other data from the soil analysis as explanatory variables for Mean C and FQI values. We limited the trees to three splits with a minimum of two plots per cluster. Keeping the number of plots per cluster as low as possible allows the model to best identify extreme values at any given node.

2.3.4. Univariate regression

To examine relationships between metals concentrations and floristic quality, we used univariate least-squares linear regression of Mean C and FQI against natural log (ln) transformed Pb and Zn concentrations in the topsoil, subsoil and averaged between subsoil and topsoil (mean soil concentration) using SYSTAT v. 11 (Systat Software, Inc., 2004).

3. Results

3.1. Plot soil variables and floristic quality

Soil concentrations for Pb ranged from 12 mg/kg to 3679 mg/kg; those for Zn ranged from 21 mg/kg to 1276 mg/kg (Table 1). The lowest Mean C (3.30) was recorded at plot B-2, which had the second highest mean Pb concentration (2245 mg/kg) and the fifth highest mean Zn concentration (627 mg/kg). The lowest FQI (22.6) was recorded at plot D-4, which had the third highest mean concentrations of Pb (1080 mg/kg) and Zn (667 mg/kg). The highest Mean C was documented in plot I-2, with mean Pb and Zn concentrations of 62 mg/kg and 106 mg/kg, respectively; the highest FQI was in plot D-3, with a mean Pb concentration of 300 Mg/kg and a mean Zn concentration of 164 mg/kg. Topsoil and subsoil variables for all plots are provided in Table 1; floristic quality measures are provided in Table 2.

Exotic species were documented in 19 of the 44 plots. The highest exotic to native richness ratio (0.15) and the highest exotic to native cover ratio (0.56) were documented at plot B-1, which also had the highest Pb concentration (3464 mg/kg) and second highest Zn concentration (851 mg/kg). A list of species encountered during the study, including their C values and their status as native or introduced (Ladd, 1993) is provided in Appendix 1 (supplemental electronic data).

3.2. Nonmetric Multidimensional Scaling ordination

Analysis of data using NMS yielded a two-dimensional solution with a final stress of 11.2 ($p = 0.004$; Fig. 2). Axis 1 explained 74 percent of the variation, while Axis 2 explained 15 percent of the variation. The dependent variables with the strongest correlation to the overall data structure were Mean C ($R^2 = 0.67$), the ratio of exotic species richness to native species richness ($R^2 = 0.50$), and exotic species richness ($R^2 = 0.46$). Among explanatory variables, soil Pb and Zn soil concentrations had six of the eight highest correlation values ($R^2 > 0.31$). Correlation vectors (arrows) for variables with R^2 values above 0.40 in the NMS joint plot (Fig. 2) illustrate the negative relationship between metals concentrations and Mean C and the positive relationship between metals concentrations and exotic species abundance. Relationships between FQI and metals concentrations were also negative, though weaker (not shown).

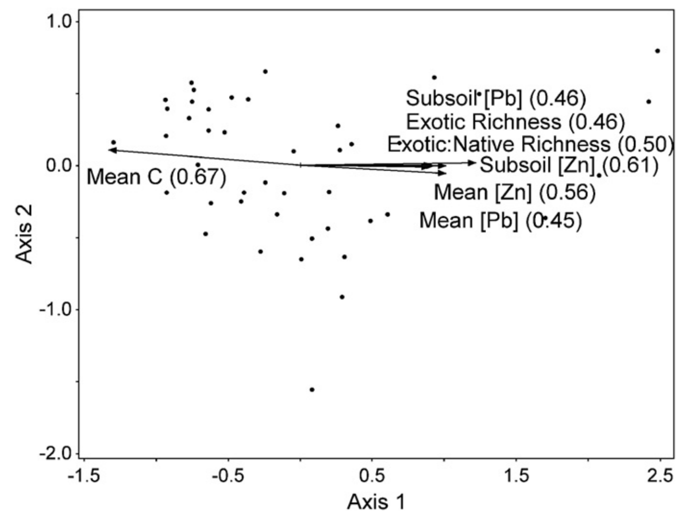

Fig. 2. PC-ORD NMS output showing those variables most correlated with community composition in the Southeast Missouri Mining District, Missouri, USA (multiple R^2 values are indicated in parentheses).

3.3. Regression trees

least-squares regression trees explained 61 and 64 percent of the variation in Mean C and FQI, respectively (Table 3). Regression trees for Mean C identified only metals concentrations (topsoil Zn, subsoil Pb and topsoil Pb) as the principal explanatory variables with roughly equal fit values for all three variables (Table 3). Both the Mean C and the FQI regression trees selected the same group of six plots at the first cut, with higher mean floristic quality values in clusters with topsoil Zn less than 615 mg/kg (Fig. 3). Subsequent divisions within the Mean C model selected soil Pb concentration variables (subsoil Pb at 34 mg/kg and then topsoil Pb at 213 mg/kg) as the primary explanatory variables. Subsequent divisions in the FQI model selected topsoil and subsoil cation exchange capacity (CEC) as explanatory variables.

3.4. Univariate regression

Univariate regression results for topsoil, subsoil and mean soil concentrations were similar for both Pb and Zn analyses; for

Table 3
Least-squares regression tree splits, explanatory variables, and cut values for Mean C and FQI.

Split	Variable	Cut value	PRE[a]	Fit
Mean C				
1	Topsoil Zn (mg/kg)	615.7	0.41	0.41
2	Subsoil Pb (mg/kg)	34.3	0.53	0.37
3	Topsoil Pb (mg/kg)	212.7	0.61	0.41
FQI				
1	Topsoil Zn (mg/kg)	615.7	0.33	0.33
2	Topsoil CEC (meq/100 g)	12.0	0.53	0.33
3	Subsoil CEC (meq/100 g)	7.7	0.64	0.46

[a] proportional reduction in error; final value estimates the variation explained by the overall model.

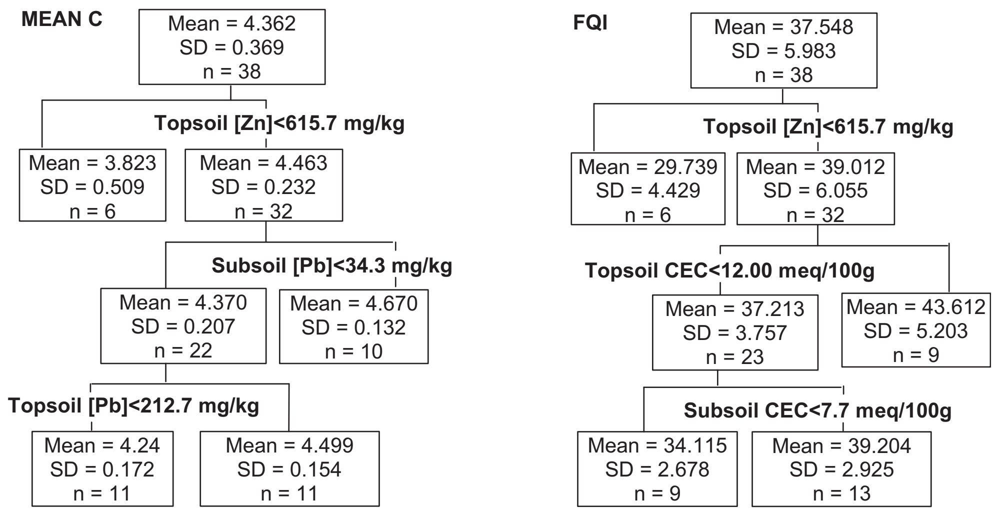

Fig. 3. Least-squares regression trees showing the top three variables that explain variation in Mean C (left) and FQI (right) of plant communities in the Southeast Missouri Mining District, Missouri, USA.

simplicity, only results for mean soil metals concentrations are presented. Univariate least-squares linear regression indicated significant negative relationships between both Mean C and FQI and mean ln-transformed concentrations of Pb and Zn in the soil ($p < 0.05$; Fig. 4). The negative relationships were stronger (greater R^2 values) for Mean C than for FQI.

4. Discussion

Soil concentrations of Pb and Zn found in this study were well within ranges identified by other studies in the area (U.S. Environmental Protection Agency, 2006). Results from both NMS and regression tree analyses indicate that Pb and Zn soil

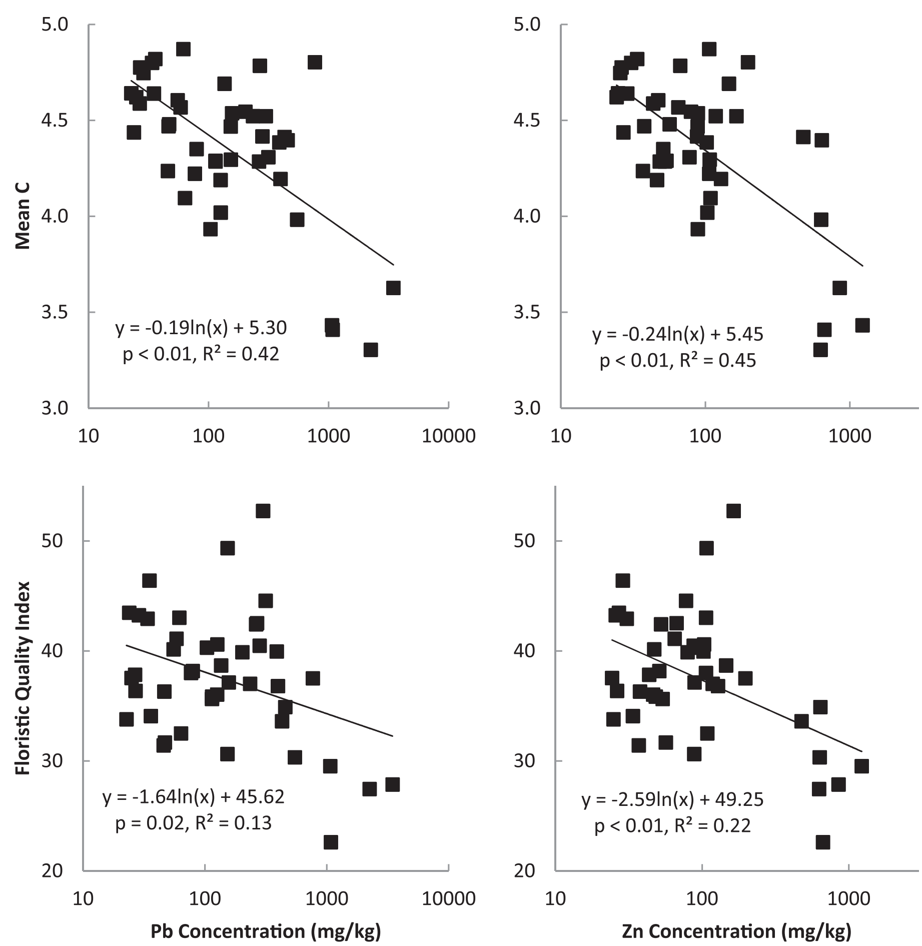

Fig. 4. Least-squares linear regression of Mean C (top) and FQI (bottom) against ln-transformed mean concentrations of Pb (left) and Zn (right) for plant communities of the Southeast Missouri Mining District, Missouri, USA.

concentrations are among the most important factors associated with floristic quality within the study area. The low stress value and the high percentage of variation explained by the two axes in NMS allow us to confidently conclude that there are strong negative relationships between metals concentrations and floristic quality measures. This conclusion is corroborated by evidence from regression trees that identify soil Pb and Zn concentrations as primary explanatory variables for community-level effects of floristic quality, with lower quality flora occurring in plots with higher metals concentrations in the first two cuts. Finally, univariate least-squares linear regression demonstrates significant negative relationships between floristic quality measures and soil Pb and Zn concentrations.

The regression models can be used to predict soil metals concentrations at which specific percent reductions in floristic quality measures might occur. For example, in Table 4, we present estimated floristic quality values (Y_b) for background soil metals concentrations within the study area (NewFields, 2006), ten percent reductions from these estimated values ($0.9Y_b$), and concentrations at which ten percent reductions are predicted ($X_{0.9Yb}$). These calculations suggest that ten percent reductions in floristic quality will be expressed at lower soil Zn concentrations than soil Pb concentrations.

The Zn concentrations associated with 10 percent reductions in floristic quality are similar to predicted concentrations obtainable from other research (similar phytotoxic comparisons for Pb are not available). A model by Beyer et al. (2011) predicts a ten percent reduction in tree seedling density at concentrations as low as 132 mg/kg, suggesting that, in young plants, lethal effects of Zn can become evident at very low concentrations. These concentrations are similar to those at which reductions in root mitotic activity has been observed (Pahlsson, 1989). Other models by Beyer et al. (2011) predict ten percent reductions in tree, shrub and vine cover at Zn concentrations between 600 mg/kg and 850 mg/kg, concentrations at which enzyme activity for photosynthesis and hydrolysis is reduced (Pahlsson, 1989). Together, these models identify soil zinc concentrations that may affect mortality, vigor, or both, even in mature trees and shrubs. Nash (1975) identified a critical Zn concentration of 200–600 mg/kg, above which significant reductions in lichen diversity are likely, and a regression equation from Pierzynski and Fick (2007) predicts a ten percent reduction in species richness at a Zn concentration of 215 mg/kg. Concentrations of Zn in excess of these are frequently encountered adjacent to mine waste within the study area. More generally, the models presented here can be used as ecological screening tools to identify locations within the mining districts where contamination from mining activities is likely to have adverse effects on plant communities.

It is important to note that a species' C value is not a measure of the value of that particular species as a provider of food, cover, habitat, or other ecological service, but rather a measure of sensitivity to disturbance, in this case, heavy metals introduced to soils from mine waste or smelting. It is also important to note that, because both Mean C and FQI are calculated on species presence/absence data rather than size or physical condition of species, neither is able to capture non-lethal effects of disturbance. In this study, negative non-lethal effects of metal contamination are evident in the positive relationships between metals concentrations and the ratio of exotic species cover to native species cover.

Our findings of lower Mean C and FQI and increasing richness and abundance of non-native species on sites with higher Pb and Zn soil concentrations support earlier research documenting the negative effects of elevated metals concentrations on plant community composition and structure. Previous work in the United Kingdom has demonstrated that community richness and species composition are negatively affected by increasing soil Zn and Pb concentrations (Clark and Clark, 1981; Thompson and Proctor, 1983). Nash (1975) and Beyer et al. (2011) documented negative relationships between Zn concentrations and the richness and cover of vascular plants and lichens near a smelter in the Appalachian Mountains. In Montana, LeJeune et al. (1996) documented reduced structural and compositional heterogeneity associated with metals contamination on floodplains. Within the Tri-State Mining District of the central United States, Pierzynski and Fick (2007) documented negative relationships between soil Zn concentration and species richness and biomass; and Kindscher et al. (2008) documented higher floristic quality on reference sites compared to sites contaminated with chat and other mine waste.

This study represents an expansion of the types of disturbance for which Floristic Quality Assessment has been used and an expansion of the analytical methods applied to floristic quality data. In wetlands, the disturbances of interest affecting floristic quality typically have been hydrologic alteration or changes in surrounding land use (Lopez and Fennessey, 2002; Mushet et al., 2002). Studies in prairies have identified grazing and other on-site management practices as the dominant disturbance mechanisms affecting floristic quality (Higgins et al., 2001; Rothrock and Homoya, 2005). The only other study using Floristic Quality Assessment in the context of mining contamination did not isolate metal contamination from other disturbances associated with mining (Kindscher et al., 2008). Regarding the analytical approach, the use of continuous data for the disturbance variable (rather than *a priori* classes, as in: Higgins et al., 2001; Lopez and Fennessey, 2002; Mushet et al., 2002) provides an objective measure of disturbance (continuous data on metals concentrations) without which it would have been impossible to perform the multivariate and regression analyses reported here.

Within the context of metals contamination, Floristic Quality Assessment could provide a valuable tool for restoration monitoring, a potential application first identified by Swink and Wilhelm (1994). Subsequent researchers have concluded that floristic quality tends to increase with time since restoration (McIndoe et al., 2008; Mushet et al., 2002) and that restored sites rarely attain the floristic quality of undisturbed sites (Mushet et al., 2002;

Table 4
Calculated concentrations (mg/kg) for 10% reductions in Floristic Quality Assessment (FQA) measures compared to modeled values at background soil metals concentrations for the Southeast Missouri Mining District.

FQA measure (y)	Model x = metal concentration	X_b background concentration[a]	Y_b predicted value at X_b	$0.9Y_b$ 10% reduction from Y_b	$X_{0.9Yb}$ concentration at $Y_{0.9Yb}$
Pb					
Mean C	$y = -0.19 \ln(x) + 5.30$	62	4.52	4.06	661
FQI	$y = -1.64 \ln(x) + 45.62$		38.86	34.97	663
Zn					
Mean C	$y = -0.24 \ln(x) + 5.45$	71	4.43	3.98	448
FQI	$y = -2.59 \ln(x) + 49.25$		38.22	34.40	311

[a] NewFields, Inc., 2006.

Rothrock and Homoya, 2005). The regression models presented here can identify target floristic quality values for restoration sites across a range of metals concentrations, and Floristic Quality Assessment can be used to determine whether those targets are being met by restoration activities. Even in regions without the necessary information on local coefficients of conservatism, floristic quality measurements such as exotic species richness and the ratio of exotic to native species richness can easily be quantified; they are strongly associated with soil metals concentrations in this study.

5. Conclusion

The research presented here demonstrates negative community-level effects resulting from contamination by heavy metals. Our research indicates that metals concentrations are more critical determinants of floristic quality than are other soils factors, and that Zn and Pb concentrations and floristic quality are inversely related. Species that are least tolerant of disturbance are most negatively affected by increasing metals content in the soils, and Floristic Quality Analysis can be a useful tool for determining community-level effects of soil metals contamination. Finally, when considering conservation strategies for native species, heavy-metals contamination must be considered among the long list of anthropogenic disturbances influencing a site.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.01.021.

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