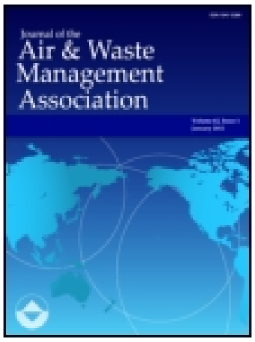

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Lead Contamination of the Roadside Ecosystem

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The atmospheric, edaphic, and vegetative components of the roadside ecosystem contain elevated levels of lead originating from the combustion of lead containing gasolines by motor vehicles. The size of this ecosystem approximates 3.04 × 10^7 hectares (118,000 square miles) in the United States. Recent evidence has greatly refined our understanding of the distribution and localization of lead in the roadside environment. This paper is a representative review of some of this recent evidence. Vehicles release approximately 80 mg of lead/km to the atmospheric compartment in the form of inorganic lead salts ranging in size from 1 to 5 μ. Lead content of roadside atmospheres may be elevated 2–20 times non-roadside atmospheres. Sedimentation from the atmospheric compartment results in lead contamination of the soil and vegetative compartments. Lead in the upper 5 cm of the soil profile may be elevated 30 times non-roadside soil within a few m of a street or highway. The soil lead is largely bound by organic matter exchange sites or present as the relatively insoluble lead sulfate. The increased lead burden of plants, largely due to surface deposition, may be 5–20, 50–200, and 100–200 times baseline lead levels for unwashed agricultural crops, grass, and trees respectively. Invariably most plant studies demonstrate a strong inverse correlation between plant lead level and sampling distance normal to the highway and a less strong, but direct, correlation between lead burden and traffic volume. While our appreciation of the distribution of lead in the roadside ecosystem is good, our understanding of its chemistry and the effects on the biota are deficient. Acute and direct impacts of lead on components of the roadside biota are not apparent. The potential for interactive effects with other stress factors and for subtle impact is considerable, however, especially in regard to plant surface and soil microbiota, foraging insects and animals, and plant leaf and root metabolism.

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There is an extraordinary amount of literature on this important topic. Due to space constraints this review is representative rather than comprehensive. There are available excellent recent reviews that deal with one or more aspects of the topic.[1–12]

Lead is naturally present, in small amounts, in soil, rocks, surface waters, and the atmosphere. Due to its unique properties it has been an element widely useful to man. This utility has resulted in greatly elevated Pb concentrations in certain ecosystems. Locations where Pb is being mined, smelted, and refined, where industries are consuming Pb and in urban-suburban complexes the environmental Pb level is greatly elevated. With regard to the source of unnaturally occurring atmospheric Pb, the urban-suburban location is the most complex. It is widely agreed that a primary source in these sites is the combustion of gasoline containing Pb additives. Specific estimates of the amount of total Pb annually introduced to the atmosphere via gasoline combustion include 98%[9] and 95%.[5] An atmospheric inventory in Canada indicated that only 66% of the Pb was due to cars.[6] Non-automotive sources of Pb in urban-suburban environments may include coal combustion, refuse and sludge incineration, burning or attrition of lead-painted surfaces and industrial processes.

Lead in the Roadside Environment

Source

Atmospheric, terrestrial, and aquatic environments immediately adjacent to roadways are contaminated with Pb by motor vehicles combusting leaded gasoline. No controversy surrounds this observation. Perhaps the most powerful evidence stems from the use of isotopic ratios of Pb as an indication of source.[13] Common Pb consists of the isotopes ^{204}Pb, ^{206}Pb, and ^{208}Pb. Since each lead ore deposit had its isotope ratio fixed during genesis, the ratio of the isotopes can be employed to compare Pb pollutants in the environment with Pb sources.[14,15] The isotope ratios of Pb in gasoline and in aerosols, soils, and plants in the roadside environment are correlated.[16] The use of X-ray fluorescence to establish patterns of atmospheric element ratios, including Br/Pb, has also been employed to separate automotive from non-automotive Pb.[17]

Most of the gasoline sold in the U.S. and in other countries contains alkyl lead compounds to improve the antiknock quality of the fuel. The use of lead alkyls is the most inexpensive method for raising the octane rating of gasoline.[5] Between 1923 and 1964 more than 2.6×10^9 kg of Pb in the form of lead alkyls had been combusted.[14] The principal alkyl lead compound employed is tetraethyl lead [$(C_2H_5)_4Pb$]. Tetramethyl lead [$(CH_3)_4Pb$] and mixtures of the two are also employed. The amount of Pb in gasolines supplemented with lead alkyls varies from 2 to 4 g/gal. The average Pb content is approximately 2.5 g/gal.[5] Gasoline lead consumption per year has gone from approximately 90×10^6 kg in the mid-1940's to more than 220×10^6 kg in 1970.[18] Approximately 136×10^6 kg of Pb was released in automotive exhausts in 1970.[5] Since 1970 no-lead and low-lead gasolines have become increasingly available.

Not all of the lead combusted in automobile engines is released into the atmosphere. Hirschler and Gilbert[19] concluded that 25% of the Pb combusted may be held in exhaust system deposits or removed during changes of lubricating oil and oil filters. These investigators further found that lead discharged to the atmosphere varies with driving speed, driving conditions, vehicle age and fuel employed. Over many thousands of miles of driving, it is generally assumed that approximately 70–80% of the combusted Pb will eventually be released to the atmosphere. Assuming average and approximate conditions, automobiles may release up to 130 mg Pb/mi (81 mg Pb/km) into the roadside environment:

$$\frac{2.5\text{g Pb/gal} \times 0.80 \text{ emission}}{15 \text{ mi/gal}} = 0.13\text{g Pb/mi}$$

An average Pb emission rate for production vehicles of 108 mg Pb/mi has been given by Cantwell, *et al.*[20] A more conservative average emission rate of 40 mg Pb/mi has been presented by Ter Haar.[6]

Chemistry

As the lead alkyl compounds of gasoline are subjected to the elevated temperatures and pressures of combustion, they are converted to lead oxides. These oxides function to inhibit engine knock. The lead oxides react with other additives in the fuel and leave the engine as the following lead salts:[19,21]

$PbCl{\cdot}Br$
α-$NH_4Cl{\cdot}2PbCl{\cdot}Br$
β-$NH_4Cl{\cdot}2PbCl{\cdot}Br$
$2NH_4Cl{\cdot}PbCl{\cdot}Br$
$3Pb_3(PO_4)_2{\cdot}PbCl{\cdot}Br$
$PbSO_4$
$PbO{\cdot}PbCl{\cdot}Br{\cdot}H_2O$

Lead chlorobromide ($PbCl{\cdot}Br$) is generally assumed to be the primary Pb salt introduced into the atmosphere from the tailpipe.[22] The ammonium complexes are of secondary importance, with the double salt ammonium chloride-lead chlorobromide (α-$NH_4Cl{\cdot}2PbCl{\cdot}Br$) the most abundant. The fate of these Pb salts once introduced into the atmosphere is not completely understood and is controversial. Disagreement concerning the loss of halogens by these Pb compounds exists in the literature. Pierrard[23] has suggested that $PbCl{\cdot}Br$ undergoes photochemical decomposition with the formation of a lead oxide and release of free bromine and chlorine. Robbins and Snitz[24] and Ter Haar and Bayard[22] confirm the loss of halogen in newly exhausted Pb salts, but do not support the photochemical mechanism. The latter investigators suggested that lead halides are ultimately converted primarily to lead oxide and lead carbonates. Their analysis of lead compounds in a rural atmosphere (presumably aged Pb automotive emissions) revealed 30% $PbCO_3$, 27% $(PbO)_2\,PbCO_3$, 20% PbO_x, 5% $PbO{\cdot}PbSO_4$, 5% $PbCl_2$, 4% $Pb(OH)Cl$, and 3% $PbSO_4$. Several other studies provide evidence to suggest that halogens may not be lost from exhausted lead salts.[25] Boyer and Laitinen[25] evaluated the stability of laboratory pure lead halide aerosols toward halogen loss by hydrolytic exchange with H_2O, CO_2, and ultraviolet light and concluded that halogens were not lost under their laboratory (non-automotive exhaust environment) conditions.

Bomback *et al.*[26] have observed that the lead salts $PbSO_4$ and $Pb_3\,(PO_4)_2$ accumulate in catalytic converters and that deposits containing these salts may periodically break off and be exhausted.

Lead may also exist in the organic (alkyl) form in the roadside atmosphere. Fuel evaporation rather than tailpipe emission may be the primary source of this organic Pb. Laboratory exposure of simulated atmospheric dust components to tetraethyl lead vapor results in the sorption of organic Pb on dust particle surfaces.[27]

Clarification of the composition and reactions of Pb compounds leaving the tailpipe is essential to an assessment of their environmental significance. The significance of the relatively soluble lead halides will be different than the less soluble lead oxides and sulfates.

Particle Characterization

While the chemistry of exhaust Pb is complex, there is general agreement that the physical state of emitted Pb is particulate. The particulate lead compounds do, however, exhibit a rather large size variation. Hirschler and Gilbert[19] suggested that this size range extended from 0.01μ to several millimeters in diameter. Approximately one-half to two-thirds of the Pb exhausted in "city type" driving was in particles 5μ in diameter or less. Only from 4 to 12% of the exhaust Pb was 1μ or less. Under cruise conditions and at constant speed, Mueller *et al.*[28] found that 62 to 80% of the particulate Pb exhausted was less than 2μ in diameter. Of these small particles, 68% were less than 0.3μ. Habibi[29] analyzed particle size distributions under realistic operating conditions by employing a tunnel sampling system with a car operated on a programmed chassis dynamometer. He concluded that the mass median equivalent diameter (diameter of an aerodynamically equivalent sphere of unit density) of Pb particles increased significantly with increased mileage. With accumulated vehicle mileages of approximately 7000, 16,000 and 21,000 the Pb particle diameters averaged about 1μ, 4μ, and 5μ respectively. Ter Haar *et al.*[30] confirmed that exhausted Pb particles become larger as mileage accumulates and estimated over the lifetime of cars that approximately 35% of the Pb burned is emitted as fine particles ($\leqq$0.5μ) and 40% as coarse. Ewing and Pearson[5] cited median Pb particle diameters in their review of 0.24 and 0.25μ and concluded that 40% of the Pb particles in the atmosphere are <0.3μ and 95% are <0.5μ. In the immediate roadside environment (from 9–533m) of a heavily used highway (48,000 cars daily), Daines *et al.*[31] found that over 65% of the Pb in the air consists of particles under 2μ, with over 85% consisting of particles under 4μ in diameter.

Distribution

Lead is introduced into the atmospheric compartment of the roadside environment from exhaust emissions and then transferred to the soil, plant or animal compartment via sedimentation, impaction, precipitation, or inhalation. The roadside environment receives Pb particles of *all* size classes, the larger ones by sedimentation and the smaller ones by the latter three processes.

The north temperate atmosphere exhibiting the lowest Pb concentration is over the north central Pacific Ocean where the Pb concentration ranges from 0.0003 to 0.0015 μg/m^3.[32] The annual average Pb aerosol concentration at White Mountain, CA of 0.0080 μg/m^3 may be considered the baseline concentration of lead for "clean" atmospheres for the continental United States.[33] Since the major source of atmospheric Pb in most areas is gasoline combustion,[34] there is a distinct air-lead gradient that increases as one approaches aggregations of roads (urban-suburban areas), with the highest atmospheric burdens in the immediate roadside environment. Ludwig *et al.*[35] examined the annual average atmospheric Pb concentrations in 1966–67 for several remote, suburban and urban locations and suggested they were 0.022, 0.09–0.21, and 1.11 μg/m^3 respectively. In most U.S. cities the annual average concentration of Pb in air falls between 1 and 4 μg/m^3.[6,36,37] In Europe average Pb concentrations in cities ranged from 0.4 to 7.4 μg/m^3.[10] The annual average of 7 Japanese cities was 0.51 μg/m^3.[38] Maximum single sample lead concentrations in the Three City Survey[21] were 6.4 μg/m^3 in Cincinnati, 11.4 in Los Angeles, and 7.6 in Philadelphia.

Determining the movement of atmospheric Pb is particularly complex in urban areas due to multiple road sources, variable structure shapes, and complex wind patterns. Atmospheric modeling efforts at Colorado State University may help accommodate this complexity.[39–41]

The highest atmospheric Pb concentrations, however, are found in the immediate roadside environment. Maximum Pb concentrations (single measurements) recorded immediately adjacent to roadways include 89 μg/m^3 Parma, Italy,[42] 71 μg/m^3 Los Angeles, CA,[9,43] >34μg/m^3 New York City,[44] and 16 μg/m^3 U. S. Highway 1, NJ.[31] These high levels decrease rapidly as the perpendicular distance from the highway is increased. This conclusion is supported by numerous studies, two of the finest being those of Daines *et al.*[31] and Schuck and Locke.[45] Between 30 and 150 m perpendicular distance from the highways in the above studies, the atmospheric Pb loss rate/30 m was 32 and 23% respectively. In the Daines *et al.*[31] study, the Pb content of the air decreased over 50% between 3 and 46 m from the highway. At 533 m perpendicular distance 50% of the Pb containing particles greater than 6.5μ had settled out of the air. Little surface deposition, however, of the less than 3.5μ diameter particles occurred in this zone.

In addition to distance from the road, numerous other factors influence the Pb content of the atmospheric compartment of the roadside environment. Some of the most important factors include traffic volume, proximity to other roads, prevailing winds, turbulence, season of the year, and time of day. Urban atmospheres over streets may differ significantly from rural atmospheres over roadways. Edwards[27] has suggested that the "canyons" formed by multiple story buildings may restrict ventilation and occasion orders of magnitude increases in atmospheric Pb.

The effect of traffic density is limited to a relatively narrow zone (76 m) along busy highways according to the data of Daines *et al.*[31] Numerous studies have shown that if the prevailing wind direction is perpendicular to the highway, greater amounts of Pb will be distributed to the downwind or lee side of the road.[31,45,46] In seasonal studies, conducted in various United States locations, the fall months consistently exhibit the highest air Pb levels.[31,34,36,47,48] The increased fall concentrations are generally ascribed to favorable wind patterns and atmospheric mixing occurring at this time of year. Colacino and Lavagnini[49] examined atmospheric Pb in Rome, Italy and concluded that the concentration was correlated with wind velocity and direction but not with season of the year. Diurnal variations in atmospheric Pb burden close to the road generally follow the peak traffic volumes of early morning and late afternoon.[48,50]

Additional refinement of our understanding of atmospheric Pb in the roadside environment is needed. The vertical profile of Pb concentration has not been adequately studied. Skogerboe[51] has reviewed several errors of sample collection and analysis processes for atmospheric Pb that may condition the usefulness of previously acquired data. Some of the roadside atmospheric Pb is transported out of the roadside atmospheric compartment. The rest is deposited on the soil and plants of the roadside region.

Lead and Roadside Soils

Chemistry

Sedimentation and precipitation (wash-out and wash-off) act to deposit Pb particulates, perhaps primarily in the relatively soluble halide form, on the soil surface in the roadside environment. Our understanding of the chemical reactions of these particles once they are introduced into (on) the soil is very incomplete. It has been speculated for some time that Pb probably reacts with soil anions, eg. $SO_4^=$, $PO_4^{\equiv}$ or $CO_3^=$, or with some soil organic or clay complex.[52] Any of these reactions would make the Pb insoluble and preclude rapid mobility in the soil and restrict plant or microbial uptake. Little direct evidence supporting any of these reactions has been made available.

Lagerwerff and Brower[53] examined the exchange behavior of Pb^{++} present in small amounts in kaolinitic, montmorillonitic, and illitic soils pretreated with Al^{+++} or Ca^{++} and treated with various NaCl levels. In Na^+ treated, alkalized soils, Pb was precipitated. The solubility of the precipitate increased with decreasing pH and concentration of NaCl.

Table I. Lead contamination of roadside surface soils.

Traffic volume[a] (veh/24 hr)	Location	Extracting agent	Sampling depth[b] (cm)	Sampling distance perpendicular to roadway and soil lead content[c]: Closest to roadway	Midway (m)	Farthest from roadway	Constant soil lead level achieved (m)	Ref. no.
				lead(µg/g)				
56,000	Maryland	hydrochloric acid	0–5	$\frac{7.6}{122}$	$\frac{15}{75}$	$\frac{30}{63}$		61
(24,000)	Maryland	hydrochloric acid	0–5	$\frac{7.6}{403}$	$\frac{15}{211}$	$\frac{30}{92}$		61
54,700	New Jersey	perchloric acid	0–15	$\frac{7.6}{169}$	$\frac{38}{98}$	$\frac{67}{78}$		101
(12,800)	New Jersey	perchloric acid	0–15	$\frac{7.6}{134}$	$\frac{38}{60}$	$\frac{67}{58}$		101
64,180	Minneapolis-St. Paul	nitric, sulfuric perchloric acids	0–6.25	$\frac{1.5}{700}$			15	52
(1,900)	Minneapolis-St. Paul	nitric, sulfuric perchloric acids	0–6.25	$\frac{1.5}{128}$			15	52
16,000	Brisbane Australia	perchloric	0–5	$\frac{2}{145}$	$\frac{125}{30}$	$\frac{250}{25}$	25	140
(3,700)	Brisbane Australia	perchloric	0–5	$\frac{2}{130}$	$\frac{125}{20}$	$\frac{250}{20}$	25	140
7,000	Denver	nitric acid	0–15	$\frac{1.5}{500}$	$\frac{30}{30}$	$\frac{91}{30}$	15–18	141
>4,000	Illinois	unidentified	0–10	$\frac{0}{450}$	$\frac{30}{20}$	$\frac{60}{20}$	20	142
(2,000)	Illinois	unidentified	0–10	$\frac{0}{25}$	$\frac{30}{17}$	$\frac{60}{17}$	10	142
1,200	New Zealand	nitric, hydrofluoric acids	0.5	$\frac{10}{160}$	$\frac{30}{90}$	$\frac{100}{55}$		125
48,000	Maryland	hydrochloric acid	0–5	$\frac{8}{540}$	$\frac{16}{202}$	$\frac{32}{140}$		143
(20,000)	Maryland	hydrochloric acid	0–5	$\frac{8}{522}$	$\frac{16}{378}$	$\frac{32}{164}$		143
23,000	Ohio	hydrochliric acid	0–5	$\frac{8}{150}$	$\frac{16}{101}$	$\frac{32}{55}$		143
7,500	Missouri	hydrochloric acid	0–5	$\frac{8}{242}$	$\frac{16}{140}$	$\frac{32}{61}$		143
70,000	California	nitric acid	0–7.5	$\frac{15}{118}$	$\frac{197}{85}$	$\frac{364}{81}$	76[d]	144
(58,000)	California	nitric acid	0–7.5	$\frac{15}{118}$	$\frac{198}{74}$	$\frac{362}{85}$	77[d]	144
29,000	Michigan	nitric acid	0–15	$\frac{6}{150}$	$\frac{73}{50}$	$\frac{158}{50}$		96
17,500	England	nitric/sulfuric acid	0–10	$\frac{1}{130}$		$\frac{25}{80}$	50	145
Lead ore truck route	Missouri	unidentified	0–8	$\frac{11}{137}$	$\frac{46}{24}$	$\frac{259}{850}$	50	146

[a] In studies with more than one traffic volume examined, the data for the highest and (lowest) volume roads are given.
[b] In studies with more than one sample depth, the depth exhibiting the highest Pb level is given.
[c] In studies with both sides of the roadway sampled, the side exhibiting the highest Pb level is given (dry wt basis).
[d] No samples collected between 15 and 76m.

Adsorption of soil Pb by hydrous oxides of iron and manganese has also been advanced.[54]

Olson and Skogerboe[55] preconcentrated Pb compounds in roadside soil samples and employed X-ray diffraction for compound identification. In most cases, more than 50% (frequently 70%) of the Pb present occurred as lead sulfate ($PbSO_4$). Other compounds identified included $PbO{\cdot}PbSO_4$, PbO_2, PbO(?), Pb^0, and PbS. The authors could only speculate on the site of conversion of the lead halides to the insoluble lead sulfate. Conversion could occur in the atmosphere or the soil. Sulfuric acid formed in the atmosphere from SO_2 may react with lead particulates in the air to form $PbSO_4$. This reaction could also occur at the soil-atmosphere interface. Reaction with the sulfate anion may occur in the soil in contact with ground water.[56]

Distribution

Lead is transferred from the atmospheric compartment of the roadside environment to the soil compartment in a relatively narrow zone along either side of the road. Within this zone Pb is concentrated in the uppermost portion of the soil profile.

The Pb content (baseline) of the upper soil horizons of unmineralized and uncontaminated areas is generally given as approximately 10–20 µg/g, dry wt basis.[57–60] Virgin soils may vary, however, from <1 to >100 μg/g.[5] Agricultural soils may vary from 2–200 μg/g.[6] Table I summarizes the contamination of roadside soils as determined by several representative studies. If 20 μg/g is accepted as baseline, it can be seen that soil samples taken within a few m of the road surface of a heavily travelled highway may range to more than 30 times baseline. At 10 m distance from the roadway, however, the Pb level is typically only 5–15 times baseline. At approximately 20 m distance, several studies suggest that a constant level of soil Pb is achieved and the influence of the roadway is lost. Invariably investigations of roadside soil-lead conclude that the Pb concentrations are positively correlated with traffic volume and negatively correlated with perpendicular distance from the roadway. Significant variations from strict correlation occur, however, due to numerous additional variables. Since Pb accumulates in the soil, road age is important. Soil Pb adjacent to an old road with lower traffic volume may exceed soil Pb adjacent to a young road with higher traffic volume.[61] If prevailing winds blow normal to the highway, significantly higher soil Pb may be found on the lee side of the road.[61] Other important variables causing deviation from generalized correlations include: soil type, vehicle type, topography, and vegetative cover.

The vertical distribution of Pb in the roadside soil profile is restricted as is the horizontal distribution. Examination of nonroadside soil profiles with natural horizon structure has generally shown Pb concentration in the uppermost portions of the profile.[62–65] This restricted distribution is not surprising, as previously noted, because the divalent-cationic nature of Pb causes it to be bound to organic exchange surfaces abundant in the upper horizons and its reaction with $SO_4^{=}$, $PO_4^{\equiv}$ or $CO_3^{=}$ anions reduces its solubility and impedes its downward migration in the soil profile. Table II summarizes the contamination of roadside soil profiles as determined by several representative studies. While these data are characterized by considerable variation, there is a consistent reduction of Pb concentration as sampling depth is increased. Frequently the Pb content at 10–15 cm is only 25% or less of

Table II. Lead contamination of roadside soil profiles.

Traffic volume[a] (veh/24 hr)	Location	Extracting agent	Sampling distance perpendicular to roadway[b] (m)	Sampling depth and soil lead content[c]			Constant soil lead level achieved (cm)	Ref. no.
				Closest to surface	Midway (cm) lead (μg/g)	Farthest from surface		
56,000	Maryland	hydrochloric acid	7.6	0–5 122	5–10 13	10–15 15		61
(24,000)	Maryland	hydrochloric acid	7.6	0–5 403	5–10 252	10–15 121		61
54,700	New Jersey	perchloric acid	25	0–15 169		15–30 48		101
(12,800)	New Jersey	perchloric acid	25	0–15 134		15–30 82		101
16,000	Brisbane Australia	perchloric	2	3 145	12 60	25 40		140
(3,700)	Brisbane Australia	perchloric	2	3 130	12 40	25 30		140
7,000	Denver	nitric acid	e	8 40	46 25	91 20	61	141
Urban area	Champaign-Urbana	e	e	0–10 390	20–30 48	40–80 19		142
Rural area (no roads)	Illinois	e	e	0–10 16	20–30 7	40–80 4		142
1,200	New Zealand	nitric, hydrofluoric acids	10	0.5 160	3 60	6 50	6	125
48,000	Maryland	hydrochloric acid	8	0–5 540	5–10 300	10–15 98		143
(20,000)	Maryland	hydrochloric acid	8	0–5 522	5–10 460	10–15 416		143
23,000	Ohio	hydrochloric acid	8	0–5 150	5–10 29	10–15 11		143
7,500	Missouri	hydrochloric acid	8	0–5 242	5–10 112	10–15 95		143
70,000	California	nitric acid	76	0–7.5 76	25–40 83	>65 N.D.[d]	50–65	144
Urban area	Australia	acetic acid	e	0–5 17	15–30 0.7	45–60 0.4		147
12,000 (Urban area)	Illinois	e	<10	0–10 390	20–30 48	40–80 19		135

[a] In studies with more than one traffic volume examined, the data for the highest and (lowest) volume roads are given.
[b] In studies with more than one perpendicular sampling distance, the distance exhibiting the highest Pb level is given.
[c] In studies with both sides of the roadway sampled, the side exhibiting the highest Pb level is given (dry wt basis).
[d] N.D. = not detectable (<1 μgPb/gm).
[e] Not identified.

the content at 0–5 cm. Generalizations regarding roadside soil Pb correlations with specific soil horizons are difficult because these horizons are frequently unnatural or nonexistent due to disturbance associated with the construction or maintenance of the roadway.

Even though automotive Pb does not grossly pollute soils in areas apart from roads[66] and even though the chemistry of soil Pb may suggest that it is not readily available, the pervasive distribution of roads, and the Pb concentration in the upper, biologically active, strata has implications for the soil biota and justifies research interest in this topic in the roadside environment.

Effect on Soil Biota

Accumulation of heavy metals in the litter and upper soil horizons of natural forest ecosystems[67] has resulted in the hypothesis[65] that litter decomposition and nutrient cycling may be reduced in soils with excessive heavy metal input. Mechanisms proposed to account for reduced decomposition include; contamination of organic matter with persistent heavy metals, interference with soil enzymes and direct microbial toxicity.[65,68,69] Reduction of general microbial activity in soils polluted with heavy metals has been documented.[70,71] With the exception of Tyler,[72] few analyses of the litter contamination of roadside soils and microbial activity have been made. It is reasonable to speculate, however, that the rate of decomposition of soil organic matter may be reduced in the soil compartment of the immediate roadside environment. The interaction of soil lead with the nitrogen cycle[73] and the microbial transformation of iron, phosphorus, and sulfur are worthy of examination in the roadside area. Tornabene and Edwards[74] have provided *in vitro* evidence that *Micrococcus lutens* and *Azotobacter* sp. cells can take up substantial amounts of Pb with little apparent metabolic effect.

The impact of roadside soil Pb on elements of the soil fauna, including insects[75] and earthworms has been examined. The non-roadside soil earthworms, which play an important role in maintaining physical soil characteristics, do not accumulate Pb from the soil.[76] In an investigation along two Maryland highways, however, earthworms were shown to accumulate Pb. Lead concentrations decreased with increasing sampling distance from the highway and ranged up to 331 μg/g of Pb.[77] The authors concluded that animals feeding on earthworms along heavily used highways for extended periods could accumulate toxic levels of Pb. Examination of non-soil, roadside insects and arthropods have given variable results regarding lead accumulation.[78–80] Recent evidence suggests that in spite of considerable variation, Pb burden of non-soil, roadside insects does correlate with traffic volume and that the order of increasing Pb levels is: predators > chewing insects > sucking insects (personal communication—P. W. Price, Univ. Ill.). Ants may have particularly high Pb burdens. Other animals that have received attention regarding Pb levels in or associated with the roadside environment include birds,[81,82] small mammals,[83] and large mammals.[84]

A most important component of the soil biota includes the roots of higher plants. In regard to uptake of Pb by roots from the soil environment, conflicting evidence has been provided.[85–91]

Lead and Roadside Vegetation

Lead is accumulated by the vegetative component of roadside ecosystems from both the atmospheric and soil compartments. Contamination of above ground plant parts from the atmospheric compartment may be via gravity settling, impaction, or precipitation. The relative importance of these transfer mechanisms is unclear, but the first is generally considered the most important.[5,9] Contamination from the atmospheric compartment is also generally considered to be topical (superficial) in nature and largely susceptible to removal by washing.[9] Little evidence of plant Pb uptake from surface deposits has been provided. Transfer of Pb from the soil compartment to the below ground portions of plants is via root uptake from the soil solution. Since much of the Pb is presumed to be present in the soil in non- or slightly soluble forms, much of the Pb in this compartment is thought to be unavailable to roadside plants. Nevertheless, there is ample evidence that plants do take up soluble Pb through their roots.[5] The uptake is favored by low soil pH. Translocation of Pb absorbed by the roots to above ground portion of plants is controversial as the evidence is variable.

Plants that have received the greatest attention in the roadside environment include grasses, agricultural crops and woody plants.

Grasses

Lead contamination of roadside grass has been examined because of its common occurrence in the roadside ecosystem and because its use as forage may lead to animal toxicity by the consuming organism or further up the food chain.[84,92–95]

Evidence has been presented that grass receives Pb from both the atmosphere[96,97] and the soil.[98,99] Representative studies of grass contamination along roadways of varying traffic density are presented in Table III. If we assume that the Pb content of grass growing in nonroadside, relatively unpolluted environments devoid of Pb deposits is approximately $1 - 5$ μg/g[58,100,101] then considerable elevation above this baseline is evident in Table III. Close to the roadway one study found values over 900 times baseline, a more common finding, however, was approximately 50–200 times. In a non-roadside, but urban area, Purves and Mackenzie[102] found the Pb content of urban grass 3.5 times that of rural grass. Generally grass contamination varies positively (but weakly) with the traffic volume and inversely (strongly) with the sampling distance normal to the roadway.

Agricultural Crops

Agricultural crops grown in the roadside environment for human consumption have received considerable attention.[103–105] Primary concern has been the contribution roadside grains, fruits and vegetables may make to dietary lead intake. The "normal" or baseline content of Pb in vegetables has been found to be quite variable.[59,106,107] The following approximations, on a dry weight basis, have been made; 0–15 μg/g[108] and < 5 μg/g.[101,109] If the 5 μg/g level is accepted as baseline, Table IV reveals that numerous roadside crops have elevated Pb levels. One study reported corn tassel with 348 times baseline Pb level. Crop Pb levels generally, however, are less than 20 times baseline and frequently less than 10 times. The highest Pb burdens are typically not associated with the edible portion, but rather with the organ with the highest surface to volume ratio and with the roughest or most pubescent surface. Most studies have compared washed and unwashed samples and conclude that approximately 50% of the Pb is superficial and susceptible to removal by water washing.[45,110,111] The fate of the remaining 50% is unclear. Arvik and Zimdahl[112] have presented evidence to indicate that foliar uptake of Pb is not likely. Preliminary data provided by Rule *et al.*[113] however, indicate foliar absorption may occur in radish and leaf lettuce.

Lead uptake from the soil compartment may be important in agricultural crops.[114–116] The process, which may be passive,[85] is favored under conditions of low soil pH.[86] MacLean *et al.*[87] have suggested that soil management practices, including additions of organic matter, lime, and phosphate, may be appropriate in roadside soils to reduce Pb availability for root uptake. Efficiency of translocation of Pb absorbed by the roots to above-ground plant parts remains controversial. Some evidence favors translocation[117] while some does not.[118,119]

Table III. Lead contamination of roadside grass.

Traffic volume[a] (veh/24 hr)	Location	Grass species	Washing procedure	Sampling distance perpendicular to roadway and grass lead[b]			Ref. no.
				Closest to roadway	Midway (m)	Farthest from roadway	
					lead (μg/g)		
48,000	Maryland	tall fescue	light rinse	$\frac{8}{51}$	$\frac{16}{30}$	$\frac{32}{19}$	143
(20,000)	Maryland	tall fescue	light rinse	$\frac{8}{68}$	$\frac{16}{48}$	$\frac{32}{26}$	143
23,000	Ohio	orchard grass	light rinse	$\frac{8}{31}$	$\frac{16}{26}$	$\frac{32}{8}$	143
7,500	Missouri	blue grass	light rinse	$\frac{8}{21}$	$\frac{16}{13}$	$\frac{32}{8}$	143
56,000	Maryland	d	d	$\frac{7.6}{48}$	$\frac{15}{41}$	$\frac{30}{24}$	61
(24,000)	Maryland	d	d	$\frac{7.6}{60}$	$\frac{15}{56}$	$\frac{30}{40}$	61
8,000	Colorado	d	d	$\frac{1}{700^{c}}$	$\frac{152}{\sim 75^{c}}$	$\frac{305}{\sim 30^{c}}$	148
(4,300)	Colorado	d	d	$\frac{1}{\sim 300^{c}}$	$\frac{152}{\sim 30^{c}}$	$\frac{305}{\sim 50^{c}}$	148
38,000	California	wild oat	unwashed	$\frac{20}{950}$	$\frac{40}{400}$	$\frac{80}{200}$	149
(24,000)	California	wild oat	unwashed	$\frac{20}{900}$	$\frac{75}{400}$	$\frac{150}{200}$	149
54,700	New Jersey	d	unwashed	$\frac{0}{219}$	$\frac{38}{78}$	$\frac{67}{59}$	101
(19,700)	New Jersey	d	unwashed	$\frac{0}{133}$	$\frac{38}{41}$	$\frac{67}{34}$	101
19,000	Texas	various weeds	light rinse (H_2O 1 min)	$\frac{1}{106}$	$\frac{75}{12}$	$\frac{160}{7}$	150
d	Colorado	pasture grass	washed	$\frac{1.5}{222}$	$\frac{30}{57}$	$\frac{305}{28}$	58
19,267	England	d	unwashed	$\frac{1}{583^{c}}$		$\frac{25}{208^{c}}$	145

[a] In studies with more than one traffic volume examined, the data for the highest and (lowest) volume roads are given.
[b] In studies with both sides of the roadway sampled, the side exhibiting the highest Pb level is given (dry wt basis).
[c] Ash wt basis.
[d] Not identified.

Trees

Woody plants of the roadside environment have received less attention than grasses, forage or consumer crops. They are justifiably considered, however, because of their prevalence (both natural and planted) in the roadside ecosystem and their potential capacity to accumulate Pb because of their size and longevity.

The background or baseline Pb content of the twigs and foliage of shrubs and deciduous and coniferous trees is generally given as 1–4 μg/g dry weight of tissue.[58,120–123] The majority of reports suggest that levels of 1–2 μg/g are most common. Examination of Table V reveals that the outer tree surfaces (bark, twigs, leaves) of plants growing in the roadside environment may exhibit Pb contamination of 100 to 200 times this baseline level. Unlike investigations of roadside grass and crops, tree studies have generally not examined tree Pb burden along a transect extending perpendicular to the roadway. In those studies that have, however, a curvilinear decrease[46,124,125] in Pb burden with increasing distance from the highway similar to the non-tree studies has been found. Also, as in the case of grasses and agricultural crops, washing procedures have been shown to be effective in removing significant amounts of Pb from the various tree parts analyzed.[125–128] Some washing trails with woody plants, however, have been less successful in reducing lead-burden.[100,129] This may suggest that these particular washing procedures were too mild, that woody plants may hold surficial Pb more tenaciously than grasses or other crops due to rougher or more pubescent surfaces, or that the trees contain more internal Pb. The former possibilities are more probable than the latter.

Since trees are long-lived, numerous attempts have been made to use them as recorders of environmental Pb abundance over time. Because the annual wood increments of the main stem can be accurately dated, efforts have been made to correlate Pb content of the various annual rings with Pb occurrence in the environment of the tree. Working with sugar maple, red oak, and loblolly pine at several sites in Illinois, Rolfe[130] has found that stem cores taken from trees near roadways have significantly higher Pb concentrations in the last (most recent) 10 yr growth than in the earlier 10 yr growth period. Trees sampled in non-roadside environments exhibited no change in Pb content over time. Examination of the annual rings of several tree species in Palmerston North, New Zealand revealed Pb levels consistent with the introduction and use of leaded gasoline.[129] The use of stem wood to reflect historical environmental Pb levels presupposes that the Pb is not mobile in the tree stem. Stewart[131] proposed that trees may excrete toxic compounds from woody stems via translocation along radial ray parenchyma cells. Lepp and Dollard[132] employed ^{210}Pb to obtain evidence for lateral transport from bark to wood of Pb applied to the bark in several tree species.

Table IV. Lead contamination of roadside crops.

					Sampling distance perpendicular to roadway and crop lead[b]			
					Closest to roadway	Midway (m)	Farthest from roadway	
Traffic volume (veh/24 hr)	Location	Crop species	Plant part sampled[a]	Washing procedure		lead (μg/g)		Ref. no.
46,800	New Jersey	carrot	"tops"	unwashed	9 84	30 46	76 25	101
46,800	New Jersey	corn	tassel	unwashed	9 1742	30 470	76 212	101
46,800	New Jersey	lettuce	leaves	unwashed	9 120	30 47	76 23	101
46,800	New Jersey	potato	leaves	unwashed	9 368	30 171	76 95	101
46,800	New Jersey	tomato	leaves	unwashed	9 276	30 171	76 37	101
49,000	New Jersey	carrot	"tops"	unwashed	9 53	30 22	76 17	101
49,000	New Jersey	corn	leaves	unwashed	9 88	30 51	76 40	101
49,000	New Jersey	tomato	leaves	unwashed	9 88	30 52	76 44	
47,100	New Jersey	carrot	"tops"	unwashed	9 37	30 26	76 21	101
47,100	New Jersey	corn	tassel	unwashed	9 179	30 144	76 69	101
47,100	New Jersey	lettuce	leaves	unwashed	9 24	30 21	76 14	101
47,100	New Jersey	potato	leaves	unwashed	9 87	30 47	76 29	101
47,100	New Jersey	tomato	leaves	unwashed	9 76	30 82	76 40	101
12,500	New Jersey	carrot	"tops"	unwashed	9 18	30 11	76 14	101
12,500	New Jersey	corn	tassel	unwashed	9 31	30 7	76 8	101
12,500	New Jersey	lettuce	roots	unwashed	9 16	30 15	no data	101
12,500	New Jersey	potato	leaves	unwashed	9 36	30 31	76 21	101
12,500	New Jersey	tomato	leaves	unwashed	9 36	30 25	76 17	101
37,000	California	alfalfa	"top 15 cm"	unwashed	18 30	50 19	80 15	144
58,000	California	cauliflower	top half flower	unwashed	15 0.3	198 0.02	362 ND	144
48,000	California	strawberry	leaves	unwashed	5 6	97 6	189 5	144
70,000	California	tomato	fruit	unwashed	15 4	197 0.3	364 0.2	144

Holtzman,[133] however, could find little indication of circulation of ^{210}Pb in hickory and oak. Szopa *et al.*[134] concluded that black oak and shortleaf pine were not valid indicators of environmental Pb because of radial and vertical translocation of Pb. Hampp and Höll[128] have estimated that approximately 70% of the Pb present in the outer portion of a tree stem (sapwood) is fixed as lead phosphate during formation of inner stem wood (heartwood). The balance of the Pb in the sapwood (30%), however, remains mobile and may be transported laterally.

Discussion

Our understanding of Pb in the roadside environment has been greatly expanded in recent years. The primary source of Pb in this ecosystem is vehicles combusting gasoline containing lead alkyls and thereby releasing approximately 80 mg of lead/km driven. The Pb is exhausted to the atmosphere primarily as various lead salts. The chemical conversion of these salts in the atmosphere, particularly in regard to the fate of the anions, is unclear. The size of the Pb particles in the

Table IV. (Continued)

					Sampling distance perpendicular to roadway and crop lead[b]			
					Closest to roadway	Midway (m)	Farthest from roadway	
Traffic volume (veh/24 hr)	Location	Crop species	Plant part sampled[a]	Washing procedure		lead (μg/g)		Ref. no.
70,000	California	orange	fruit (peel)	unwashed	$\frac{23\text{–}30}{16}$	$\frac{120\text{–}150}{6}$	$\frac{240\text{–}270}{8}$	144
70,000	California	corn	silk	unwashed	$\frac{23}{32}$	$\frac{53}{17}$	$\frac{114}{18}$	144
70,000	California	lima bean	leaves	unwashed	$\frac{23}{99}$	$\frac{53}{83}$	$\frac{84}{35}$	144
70,000	California	red pepper	fruit	unwashed	$\frac{20}{2}$	$\frac{50}{2}$	$\frac{80}{1}$	144
70,000	California	sugar beet	leaves	unwashed	$\frac{23}{106}$	$\frac{53}{60}$	$\frac{114}{44}$	144
29,000	Michigan	lettuce	leaves	unwashed	$\frac{9}{7}$	$\frac{37}{5}$	$\frac{159}{5}$	151
29,000	Michigan	cabbage	leaves	unwashed	$\frac{9}{6.4}$	$\frac{37}{8.9}$	$\frac{159}{4.0}$	151
29,000	Michigan	tomato	fruit (?)	unwashed	$\frac{9}{1}$	$\frac{37}{1}$	$\frac{159}{2}$	151
29,000	Michigan	bean	fruit (?)	unwashed	$\frac{9}{2}$	$\frac{37}{1}$	$\frac{159}{1}$	151
29,000	Michigan	potato	fruit (?)	unwashed	$\frac{9}{0.5}$	$\frac{37}{0.6}$	$\frac{159}{0.4}$	151
29,000	Michigan	sweet corn	husk	unwashed	$\frac{9}{13}$	$\frac{37}{7}$	$\frac{159}{6}$	151
29,000	Michigan	soybean	husk	unwashed	$\frac{9}{16}$	$\frac{37}{8}$	$\frac{159}{5}$	151
29,000	Michigan	oat	chaff	unwashed	$\frac{9}{31}$	$\frac{37}{16}$	$\frac{159}{13}$	151
29,000	Michigan	wheat	chaff	unwashed	$\frac{9}{18}$	$\frac{37}{10}$	$\frac{159}{6}$	151
58,000	California	cauliflower	flower	unwashed	$\frac{15}{0.3}$	$\frac{198}{0.02}$	$\frac{364}{0.00}$	45
58,000	California	tomato	fruit	unwashed	$\frac{15}{0.6}$	$\frac{198}{0.04}$	$\frac{364}{0.03}$	45
58,000	California	cabbage	leaves	unwashed	$\frac{8}{1.1}$	$\frac{38}{<0.005}$	$\frac{69}{0.04}$	45
48,000	California	strawberry	fruit	washed	$\frac{5}{0.05}$	$\frac{96}{\text{no data}}$	$\frac{187}{0.04}$	45
48,000	California	orange	fruit (peel)	unwashed	$\frac{0\text{–}30}{3.4}$	$\frac{122\text{–}152}{1.2}$	$\frac{244\text{–}274}{1.6}$	45
Lead ore truck route	Missouri	blueberry	leaves	unwashed	$\frac{0}{98}$	$\frac{91}{45}$	no data	152

[a] The plant part exhibiting the highest level of Pb contamination is given where more than one organ or tissue was analyzed.
[b] In studies with both sides of the roadway sampled, the side exhibiting the highest Pb level is given (dry wt basis)

Table V. Lead contamination of roadside trees.

Traffic volume (veh/24 hr)	Location	Tree (shrub) species	Tree part sampled[a]	Washing procedure	Sampling distance perpendicular to roadway and tree lead[b]: Closest to roadway	Midway	Farthest from roadway	Ref.
					(m) / lead (µg/g)	(m) / lead (µg/g)	(m) / lead (µg/g)	
24,000	Connecticut	eastern white pine	needles plus twigs	unwashed	6 / 212	12 / 170	24 / 125	46
13,000	Georgia	tree-of-heaven	leaves	washed	6 / 50		24 / 30	153
1,200	New Zealand	cottonwood (shrub, *Cassinia vauvilliersii*)	leaves	unwashed	1–6 / 826[c]		7–12 / 350[c]	125
1,200	New Zealand	koromiko (shrub, *Hebe odora*)	leaves	unwashed	1–6 / 308[c]		7–12 / 250[c]	125
11,500	New Zealand	European ash	leaves	unwashed	0 / 440[c]			129
11,500	New Zealand	English elm	leaves	unwashed	0 / 860[c]			129
11,500	New Zealand	horse chestnut	leaves	unwashed	0 / 520[c]			129
11,500	New Zealand	English oak	leaves	unwashed	0 / 920[c]			129
11,500	New Zealand	London plane	leaves	unwashed	0 / 1,060[c]			129
11,500	New Zealand	sycamore	leaves	unwashed	0 / 900[c]			129
12,000	Illinois	sugar maple	wood (increment cores, last 10 years)	unwashed	10 / 11		100 / 1.5	130
12,000	Illinois	red oak	wood (increment cores, last 10 years)	unwashed	10 / 8.5		100 / 2	130
lead ore—truck route	Missouri	eastern red cedar	leaves plus twigs?	unwashed	9 / 1500–20,000[c]			154
2,100[d]	Germany	black locust	bark	unwashed	0–1? / 95			128
700[d]	Germany	black locust	bark	unwashed	0–1? / 29			128
lead ore—truck route	Missouri	black oak	bark	unwashed	0–3? / 250			134
lead ore—truck	Missouri	shortleaf pine	bark	unwashed	0–3? / 170			134
~6,000	Sweden	Norway spruce	needles	washed	5 / 20	40 / 12	80 / 5	124
1,000[d]	Switzerland	fir	needles	unwashed	0–3? / 750			127
200[d]	Switzerland	fir	needles	unwashed	0–3? / 75			127
variable (urban area)	Connecticut	pin oak	leaves	unwashed	1 / 140			155
variable (urban area)	Connecticut	sugar maple	twigs	unwashed	2 / 149			155
variable (urban area)	Connecticut	Norway maple	leaves	unwashed	2 / 156			155
variable (urban area)	Connecticut	eastern hemlock	twigs	unwashed	4 / 295			155
variable (urban area)	Connecticut	yew	twigs	unwashed	4 / 160			155
variable (urban area)	Connecticut	Norway spruce	twigs	unwashed	5 / 258			155
lead ore—truck route	Missouri	white oak	leaves	[e]	11 / 87	61 / 24	305 / 10	146
lead ore—truck route	Missouri	blueberry	leaves	[e]	11 / 100	30 / 25	305 / 13	146
variable (urban area)	Germany	Norway maple	leaves	unwashed	1 / 162	60 / 82	120 / 80	156

[a] The plant part exhibiting the highest level of Pb contamination is given where more than one organ or tissue was analyzed or where more than one sampling position was employed.

[b] In studies with both sides of the roadway sampled the side exhibiting the highest Pb level is given (dry wt basis)

[c] Ash wt basis

[d] Veh/hr

[e] Not identified.

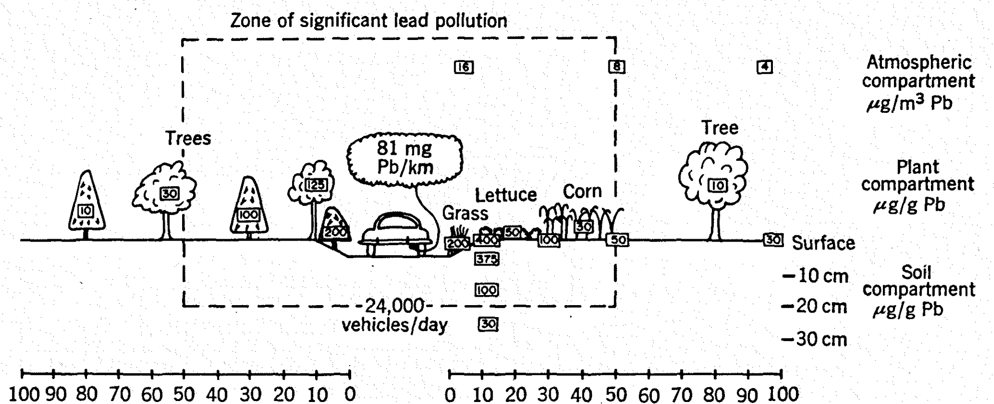

Figure 1. Compartmentalization of automotive exhaust lead in the atmospheric, vegetative and soil components of a hypothetical roadside ecosystem bisected by a roadway averaging 24,000 vehicles per day.

atmospheric component of the roadside environment is variable, but small. Significant numbers are less than 1μ in diameter with most less than 5μ. The urban atmospheric Pb content in the U.S. varies between 1–4 $\mu g/m^3$. Levels in the immediate roadside environment, particularly in urban "canyons" may be many times this level. Atmospheric Pb load decreases precipitately as the perpendicular sampling distance from the road is increased such that approximately one-half or more of the Pb is removed by 50 m distance.

Lead is transferred from the atmosphere to the soil and vegetative compartments of the roadside ecosystem by sedimentation and precipitation. In the soil compartment Pb is concentrated in the upper few cm of the profile where it is primarily bound by organic matter. The most abundant Pb salt in the soil may be the relatively insoluble $PbSO_4$. Within a few m of either side of a busy roadway soil Pb may be 30 times nonroadside soil. Much variability exists in the literature and may reflect various analytical techniques. R. K. Skogerboe (Colorado State Univ—personal communication) feels many soil Pb estimates may be low due to inappropriate extraction. The soils adjacent to roads with less than 1000 vehicles in 24 hr do not exhibit elevated Pb levels.[135] Soil Pb decreases rapidly as the perpendicular distance from the road is increased with little elevation beyond 20–30 m.

Plants growing in the roadside ecosystem are contaminated with Pb primarily on their above-ground external-surfaces via gravity settling of Pb particles. Agricultural crops, for example vegetables, may exhibit Pb burdens 5–20 times non-roadside crops. Roadside grass may contain 50–200 times the Pb associated with non-roadside grass. Trees in the roadside ecosystem may exhibit Pb contamination approximately 100–200 times baseline levels. A generalized compartmentalization of Pb in the roadside ecosystem of a medium duty highway is presented in Figure 1. The "ecosystem" approach to lead distribution is very informative and has been undertaken in an Illinois study.[136]

Despite our considerable awareness of the amount and localization of Pb in the roadside area, we remain quite ignorant regarding its chemistry and function. What is the relationship between soil Pb and soil microorganisms? Is the rate of organic matter decomposition altered by Pb? Does soil Pb influence the metabolism or ecology of soil insects and animals? With regard to vegetative contamination, what is the influence of surficial Pb on plant surface microflora and foraging insects and animals? What is the chemistry of Pb on the surfaces and internal tissues of plants? Where is the Pb specifically localized? Hampp and Ziegler[137] have suggested that Pb associated with plant surfaces in nature may be largely lead phosphate. These authors have found Pb accumulation in spinach-leaf guard-cells when they treated with lead nitrate. Does soil Pb influence seed germination or root development in nature? Does Pb reduce photosynthesis, pollen production, and germination, flowering or fruit set in nature?

Does Pb interact with other environmental stresses, for example de-icing salts or acid precipitation, to cause synergistic, additive or antagonistic responses in vegetation? How effectively do woody plants "filter" roadside air[138,139] and is this long or short term capability?

Many of the roadside investigations reviewed, examined rural or suburban highways. Urban roadside ecosystems may differ substantially because of their peculiar meteorology and proximity to other pollution sources. Our study[100] of urban roadside trees revealed excessive contamination with Zn, Fe, and Na in addition to Pb. The significance of Pb to the roadside biota is apparently subtle, undoubtedly complex (Figure 2) and worthy of continued investigation. If one assumes that there are approximately 3.04 × 10^6 km of roads with more than 1000 vehicles using them per day and that the Pb influence may extend to 50 m on either side of the roadway, then the size of the roadside ecosystem in the U.S. with elevated Pb may approximate 3.04 × 10^7 hectares or 118,000 square miles.

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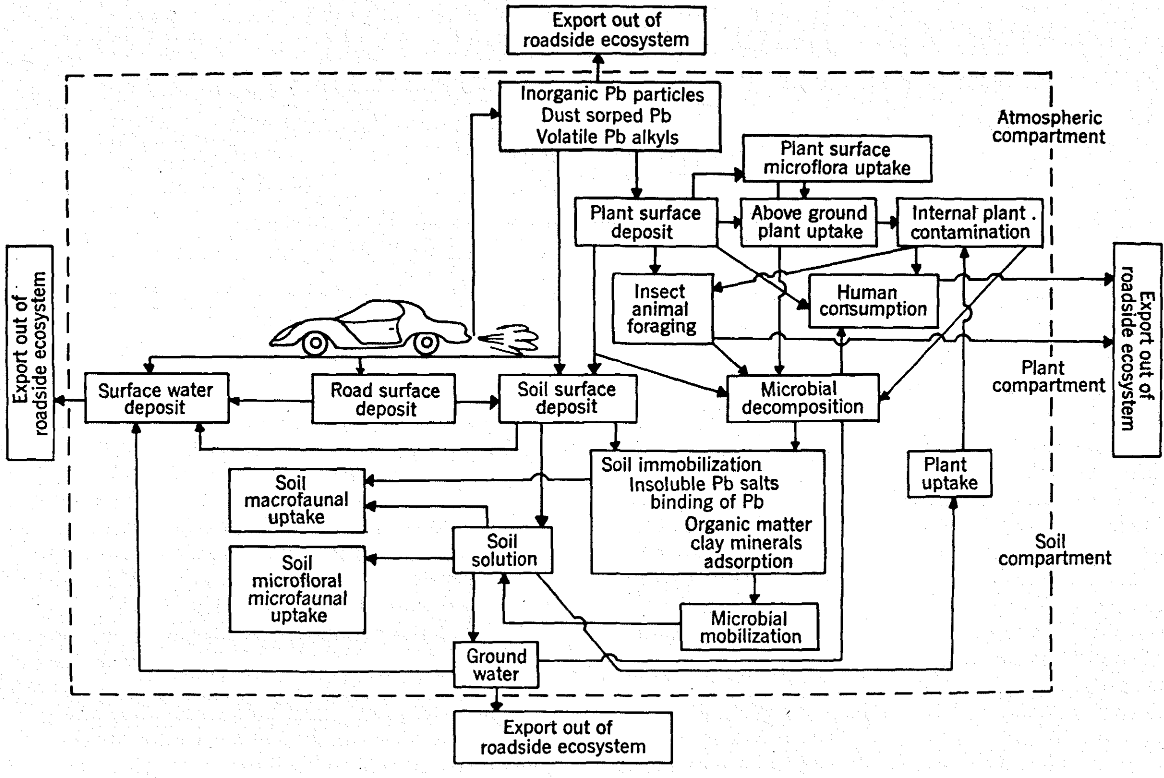

Figure 2. Potential lead distribution and transfer routes in the roadside ecosystem.

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