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REVIEWS AND ANALYSES

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Polycyclic Aromatic Hydrocarbons (PAH's) in the Terrestrial Environment—A Review[1]

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ABSTRACT

This review, while touching on sources of polycyclic aromatic hydrocarbons (PAH's) and their degradation, emphasizes research that addresses their fate in the terrestrial environment. Typical endogenous concentrations of PAH's in soil and vegetation range from 1 to 10 μg/kg and from 10 to 20 μg/kg, respectively. Endogenous PAH's are due to plant synthesis, forest and prairie fires, volcanoes, etc. Anthropogenic sources are primarily from fossil fuel burning. Estimated annual release of benzo(a)pyrene (BaP) from fossil fuel combustion is 4.6×10^4 kg. Concentrations of PAH's in air, soil, and vegetation vary with distances from known sources. Reported BaP concentrations in air of nonurban areas of the United States ranged from 0.01 to 1.9 μg/m³; concentrations in urban areas ranged from 0.1 to 61.0 μg/m³. Concentrations of BaP in soil may typically reach 1000 μg/kg, and values exceeding 100 000 μg/kg have been reported near known sources. Typically, concentrations for total PAH's (usually the sum of 5 to 20 PAH's) exceed BaP concentrations by at least one order of magnitude. The maximum PAH concentration in vegetation growing near a known source was 25 000 μg/kg, but values more typically range from 20 to 1000 μg/kg. Reported BaP concentrations in vegetation ranged from 0.1 to 150 μg/kg. Concentrations in vegetation were generally less than those in soil where the plants were growing. Concentration ratios (concentration in vegetation/concentration in soil) ranged from 0.0001 to 0.33 for BaP and from 0.001 to 0.18 for the sum of 17 PAH's tested. However, laboratory experiments demonstrated that plants can concentrate PAH's above those found in their environment. Controlled experiments with a few PAH's demonstrated uptake by both leaves and roots and subsequent translocation to other plant parts. Washing leaves of vegetation contaminated with PAH's removes no more than 25% of the contamination. There is some evidence that plants can catabolize PAH's, but metabolic pathways have not been defined well.

Additional Index Words: **Benzo(a)pyrene, carcinogens, vegetation, soil plant uptake, sources.**

Edwards, N. T. 1983. Polycyclic aromatic hydrocarbons (PAH's) in the terrestrial environment—a review. J. Environ. Qual. 12:427-441.

Polycyclic aromatic hydrocarbons (PAH's) occur naturally in the environment, primarily as a result of synthesis by some plants and formation during natural forest and prairie fires. However, by far the greatest amounts of PAH's released into the environment are formed during fossil fuel combustion and during anthropogenic forest and agricultural fires. The carcinogenic nature of some PAH's led to considerable research into their behavior in the aquatic environment, but relatively little research has been conducted on their fate in the terrestrial environment. Results of research on the movement of PAH's into vegetation directly from the atmosphere and indirectly from soil is somewhat contradictory. However, recent findings indicate that there is a potential for their accumulation in the terrestrial food chain. Most of the research has been on benzo(a)pyrene (BaP), a known carcinogen. The need for more research on a number of carcinogenic PAH's in the environment and an evaluation of research already conducted becomes increasingly important as the combustion of fossil fuel increases to keep pace with

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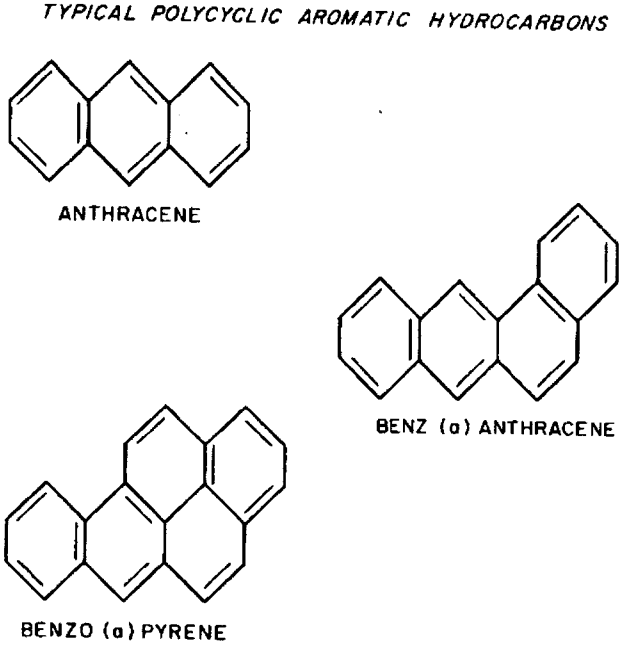

Fig. 1—Typical polycyclic aromatic hydrocarbons.

the world's energy needs. This report presents a brief review of PAH sources and some of the findings from research on soil and terrestrial vegetation contamination and plant assimilation of PAH's.

CHEMISTRY AND BIOLOGICAL ACTIVITY

Polycyclic aromatic hydrocarbons are made up of three or more fused benzene rings in linear, angular, or cluster arrangements and contain only C and H (Fig. 1). They are formed whenever organic substances are exposed to high temperatures and may also be synthesized by some plants and bacteria (Blumer, 1976). Most PAH's are practically insoluble in water. Boiling points of 14 of the more commonly studied PAH's range from 150 to 525°C and melting points range from 101 to 438°C (NAS, 1972). Molecular weights of 40 PAH's listed by the National Academy of Sciences (1972) ranged from 178 to 300. Eleven of the forty were listed as being strongly carcinogenic or mutagenic, and 10 were listed as weakly carcinogenic or mutagenic. There is some evidence that PAH's may react with NO_2 in the atmosphere to form mutagenic nitro derivatives. Pitts et al. (1978) demonstrated the formation of nitrobenzo(a)pyrene when BaP was exposed to NO_2 containing traces of nitric acid and that perylene (a noncarcinogen) was converted to 3-nitro-perylene with similar exposure. The 3-nitro-perylene was shown to be an active mutagen.

Relatively little is known about the biological activity of PAH's. The well-known PAH's such as BaP are innocuous by themselves, but can be biologically activated by enzymes to form epoxides that are carcinogenic and mutagenic (Levin et al., 1978). Conversely, recent discoveries indicate that some green plants contain a substance (ellagic acid) that can destroy the diol epoxide form of BaP, inactivating its carcinogenic and mutagenic potential (Sayer et al., 1982).

Table 1—Estimated annual benzo(a)pyrene (BaP) and polycyclic organic matter (POM) emissions to the atmosphere. Values in parenthesis are percentages of total.

	BaP (kg × 10^6)		POM (kg × 10^6)†
Sources	United States‡	Global§	Global¶
Heating and power	0.43 (36.8)#	2.36 (51.6)#	208.65 (4.8)
Industrial processes	0.18 (15.4)††	0.95 (20.8)††	
Enclosed incineration	0.03 (2.6)	0.09 (2.0)	390.09 (9.0)
Coal refuse burning	0.31 (26.5)	0.62 (13.6)	
Forest and agricultural fires	0.13 (11.1)	0.38 (8.3)	3256.78 (75.1)‡‡
Other refuse burning	0.07 (6.0)	0.13 (2.8)	480.81 (11.1)
Trucks and buses	0.01 (0.8)	0.03 (0.7)	
Automobiles	0.01 (0.8)	0.01 (0.2)	
Total	1.17	4.57	4336.33

† Polycyclic organic matter.
‡ From National Academy of Sciences, 1972.
§ From Suess, 1976.
¶ From Kornreich, 1975.
# 91% from coal and 8% from wood.
†† 99% from coke production.
‡‡ 60% from agricultural burning and 40% from natural forest fires.

SOURCES OF PAH's

Sources of PAH's to the terrestrial environment are both natural (e.g., forest and prairie fires, volcanoes, and synthesis by plants and microorganisms) and anthropogenic. The latter sources originate primarily during the combustion of fossil fuels by electric power plants, refuse burning, and agricultural burning (Table 1).

Natural Sources[3]

Andelman and Suess (1970) reviewed the literature on sources of PAH's and concluded that the ubiquitous nature of PAH is a consequence of synthesis in terrestrial vegetation. They cite one reference that reports BaP concentrations of 1000 μg/L of crude petroleum oil. This suggests synthesis by plants or formation during the natural conversion of biomass to oil. Suess (1976) and Shabad (1980) pointed to microbial synthesis, higher plant synthesis, and volcanic activity as major contributors to the natural background levels of PAH's, but emphasized that quantities of PAH's formed by natural processes are very small in comparison with those from anthropogenic sources.

Blumer (1961) suggested that PAH's found in rural soil remote from major highways and industries cannot be attributed totally to air pollution, but are instead endogenous to soil. However, Lunde and Bjorseth (1977) demonstrated that PAH's are transported over relatively long distances from industrial areas of England, France, and Scotland. After analyzing complexes of PAH assemblages in soils and recent marine sediments, Youngblood and Blumer (1975) concluded that these compounds originated from natural forest and prairie fires and were then dispersed in the atmosphere. Graf and Diehl (1966), analyzing rye, wheat, and lentils that had been grown in PAH-free nutrient solution, provided evidence favoring an endogenous synthesis of PAH by terrestrial plants. However, Grimmer and Duvel (1970) found that plants grown in filtered air contained no detectable PAH's, while their counter-

[3] See the Appendix for scientific names of plants used in text and tables.

parts in unfiltered air did contain PAH's. Graf and Nowak (1966) observed that BaP and other PAH's stimulated the growth of algae and higher plants—tobacco, rye, and radish—grown in solution culture, and suggested that PAH's synthesized by plants may act as plant growth hormones. Wettig et al. (1976) germinated several species of vegetable and grain seeds in hydroponic systems, with and without an added C source, and found that the seeds with the added C increased in BaP content. Borneff et al. (1968a, 1968b) demonstrated that algae can synthesize PAH's from ^{14}C-acetate added to their growth medium.

Anthropogenic Sources

Andelman and Suess (1970) reviewed the literature on the origin of PAH's and their transfer to the environment, with emphasis on the aquatic environment. Their review showed that the origin of most PAH's is through high temperature pyrolysis of various naturally occurring organic materials (e.g., coal). Major sources to the water environment included coal tar, coal-tar pitch, shale oil, C black, cracked mineral oil effluents from various industrial processes, and sewage sludge. While all of these are also potential sources of PAH's to terrestrial vegetation (especially sewage sludge that is used as a soil conditioner and fertilizer), the main source of contamination of the soil by PAH's is by deposition from air (Suess, 1976). Suess estimated global BaP emissions during 1966–1969 of about 4.6×10^6 kg/y, mostly from fossil fuel burning, with motor vehicles contributing only about 1% of the total (Table 1).

Much greater amounts of polycyclic organic matter (POM) that contains BaP and other PAH's are released from forest and agricultural fires than from fossil fuel burning (Kornreich, 1975). According to Suess (1976), only 8% of the global release of BaP is from forest and agricultural burning; according to Kornreich (1975), 75% of the global release of POM is from forest and agricultural burning, with fossil fuel combustion contributing only 5% of the total. If these data represent reasonable estimates, we can only conclude that POM is a poor indicator of BaP release.

Shabad et al. (1971) suggested that jet aircraft exhaust is a major source of BaP. Shabad (1980) reported that a jet airplane engine emits 2–4 mg BaP/min when cruising and up to 40 000 mg/min during take off. Thus, vegetation and soil near airports often contain relatively high concentrations of PAH's (Smirnov, 1970; Audere et al., 1973). Audere et al. reported concentrations of BaP eight to nine times greater in soil, snow, and vegetation near an airport than at a control site. On a global scale, however, amounts of PAH's emitted from jet engine exhausts are very small compared with emissions from fossil fuel combustion and other sources. Using Shabad's (1980) rates and commercial jet flight data from Drysdale and Calef (1977), I conservatively estimated < 2000 kg BaP annually emitted from jet aircraft in the United States or < 0.2% of the National Academy of Sciences' (1972) estimate of total BaP emitted annually in the United States.

Blumer et al. (1977) showed that the major source of PAH's found in soils of a Swiss mountain town located in a deep valley with frequent temperature inversions was the internal combustion engine. They found concentrations of PAH's in soil close to a major highway to be greater than those in soil of the same area, but near industries. Gordon (1976), reporting on concentrations of BaP in air at various locations in Los Angeles County, Calif., concluded that PAH's in "well-ventilated" coastal areas arise primarily from automobiles, while in areas further inland, additional smaller amounts of PAH's arise from nonautomobile sources. Some of what is identified above as automobile and internal combustion engine sources probably results from the abrasion of tire and asphalt surfaces. Residential wood combustion has also been identified as a major source of PAH's in some communities (Murphy & Buchan, 1981). Gunther et al. (1967) suggested that petroleum products applied to vegetation for pest control may also be a source of PAH contamination. Hites et al. (1980) analyzed PAH content in sediment cores taken from a rural river in Rhode Island and found a distribution of PAH's that points to coal burning as a major source. They found a decrease in PAH concentrations after 1950, which reflected a change from coal to oil and natural gas as home heating fuels during the 1950's. The authors point out that returning to coal as a major energy source might have a significant effect on man's input of PAH's to the environment.

Recent Environmental Protection Agency (EPA) reports of releases of potentially hazardous chemicals from coal gasification plants support this hypothesis. Analysis of gas, liquid, tar, and solid effluents from coal-fueled gasifiers showed PAH's to be of special concern (Cleland, 1981). For example, BaP ranked near the top as a potentially hazardous chemical in the gas and tar streams, with a relatively high discharge rate in the liquid stream. Maximum discharge concentration of BaP in the gaseous stream of one of the gasifiers was 5000 μg/m^3, and the concentration in tar was 3500 μg/g. Total BaP discharged was 120 μg/g coal. Air sampling in the vicinity of a coal gasification plant in Yugoslavia showed BaP concentrations to be two to three orders of magnitude higher downwind from the plant than in other areas (Bombaugh et al., 1981).

PROBLEMS ASSOCIATED WITH EXTRACTION AND ANALYSIS

A number of experiments were performed that demonstrate that methods of sample collection and extraction may be subject to errors. Air samples collected by a cascade impactor at two sampling stations in Canada over a 5-month period contained 186 and 222% higher PAH concentrations than samples collected by more conventional, high-volume samplers (Katz & Chan, 1980). The extent of PAH degradation during air sampling may depend on the type of filter used for collecting the sample (Lee et al., 1980). Manning et al. (1981) presented data that revealed that large sampling errors can arise from particulate-only sampling devices.

Equally as important as sample collection is the efficiency of extraction and recovery. Griest et al. (1980) demonstrated low extraction efficiencies of PAH from fly ash, using ^{14}C-labeled PAH's and various extraction techniques. Moreover, additional losses of PAH can occur during purification and concentration of extracts before analysis, resulting in underestimates.

These collection and extraction problems have implications for all the data presented in this review. Also, the use of BaP as a model PAH has been so prevalent that BaP and PAH are often thought of synonymously. Suess (1976) emphasized that BaP constitutes only 1–20% of the total carcinogenic PAH's. We must be careful about general implications concerning PAH's, based on interpretations of BaP data. Katz and Chan (1980) pointed out that the use of BaP as an index of airborne PAH's may be subject to problems, especially in areas where motor vehicle traffic is one of the primary sources of air pollution. In Los Angeles, for example, the dominant PAH is benzo(ghi)perylene, a PAH with carcinogenic potential.

CONCENTRATIONS IN AIR

Concentrations of PAH's in air vary greatly, both spatially and temporally. Sawicki et al. (1960) examined the BaP content of air in 131 urban and nonurban areas of the United States. In nine large cities, the highest levels of BaP occurred during winter months and the lowest levels occurred during summer. Concentrations of BaP in the air of nonurban areas ranged from 0.01 to 1.9 ng/m^3, while concentrations in urban areas ranged from 0.1 to 61.0 ng/m^3. Pierce and Katz (1975) sampled five locations in the Toronto, Ontario, Canada area and found concentrations of BaP in air to range from 0.11 to 0.83 ng/m^3, with the highest concentrations in urban and suburban areas and the lowest concentrations in suburban-rural and rural areas. Lunde and Bjorseth (1977) and Bjorseth et al. (1979) analyzed air from a sampling station in southern Norway for 22 PAH's and determined the origins of air masses containing the PAH's from trajectories calculated from meteorological data. They found that concentrations were higher in air samples originating in England/France and northern England/Scotland (32 and 28 ng/m^3, respectively) than in air pollutants originating in northern and southern Norway (1.1 and 2.4 ng/m^3, respectively). Values for BaP ranged from 3 to 7% of the total PAH. Gordon (1976) reported the annual geometric mean concentration of 15 PAH's in air samples collected from 13 areas in Los Angeles County, Calif., to be 10.9 ng/m^3. Concentrations of BaP accounted for only 4.2% of the total. Bombaugh et al. (1981) reported maximum ambient concentrations of BaP downwind from a coal gasification plant in Yugoslavia to be $\approx$80 ng/m^3. The EPA's ambient multimedia environmental goal for BaP is 0.05 ng/m^3 (Bombaugh et al., 1981).

CONCENTRATIONS IN SOIL AND VEGETATION

Relatively few studies quantitied PAH concentrations in soil and vegetation at various distances from known sources. Most of the studies examined concentrations in soil or vegetation, but not both.

Typical concentrations of BaP in soils of the world ranged from $\approx$100 to 1000 μg/kg. A typical range for total PAH's (i.e., those quantified in the papers examined) was about 10 times the value for BaP alone. The actual measured range of BaP concentrations, including data from very highly polluted areas and from protected remote regions, is 0.4 μg/kg (Shabad et al., 1971) to 650 000 μg/kg (Fritz, 1971). However, BaP concentrations exceeding 1300 μg/kg were very close to known sources (Shabad, 1968; Shabad et al., 1971; Fritz, 1971). These investigators did not analyze the soil for total PAH's. Only 10–15 PAH's were known or suspected to be present in soils in the late 1960's, but with recently developed analytical techniques, these numbers have increased by at least two orders of magnitude (Blumer, 1976). The highest total PAH concentration reported was 300 000 μg/kg for a soil near a highway in Switzerland (Blumer et al., 1977). Shabad et al. (1971) suggest that endogenous BaP concentrations in soil are 1–3 μg/kg and never exceed 10 μg/kg.

The first reported PAH compounds isolated from vegetation was by Guddal (1959), who extracted a mixture of PAH from roots of *Chrysanthemum vulgare* Bernh. grown in the vicinity of a gas works facility in Norway. Three PAH's were identified in the mixture as pyrene, fluoranthene, and anthracene. The concentration of the PAH (12 300 μg/kg of root tissue) was much too great to have been accounted for by plant synthesis. The only concentration reported in the literature that exceeded 12 300 μg/kg was 25 000 μg anthracene/kg orange rind collected near a heavily traveled highway in California (Gunther et al., 1967).

Concentrations of PAH's in vegetation are generally less than concentrations in the soil where they grow. Concentration ratios (conc in vegetation/conc in soil) ranged from 0.002 to 0.33 for BaP. Concentrations of BaP in vegetation ranged from 0.1 (Kolar et al., 1975) to 150 μg/kg (Fritz, 1971), with typical concentrations of 1–10 μg/kg. Only one paper reported PAH data (other than just BaP data) for both plants and soil from the same location. Wang and Meresz (1981) analyzed onions, beets, tomatoes, and soil for 17 PAH's, including BaP. They found most of the PAH contamination in the "peels." Their vegetation/soil concentration ratios ranged from 0.0001 to 0.085 for BaP and 0.001 to 0.183 for total PAH's. Graf and Diehl (1966) suggested that actively growing green plant material has an endogenous concentration of BaP of about 10–20 μg/kg and that plant storage tissues usually contain only 1–10% of that found in the green portions of the plant. Both BaP and total PAH concentrations appeared to be higher in oils extracted from plants (Stevcevska & Jovanovic-Kolar, 1974; Grimmer & Hildebrandt, 1967) than from plant tissues. This finding, if true, would have implications for certain crops growing near PAH sources, because plant organs such as seeds are important in the human diet and also contain relatively high concentrations of oils.

The amounts and kinds of PAH's ingested by humans and other animals from vegetation are partially dependent on whether particular PAH's are absorbed vs. adsorbed and how easily they are rinsed off with water. Kveseth et al. (1981) suggested that lower molecular weight PAH's are adsorbed on leaves, while higher molecular weight particulated compounds are washed off by rain. Kolar et al. (1975) found that washing vegetables removed a maximum of 25% of PAH contamination and generally less. More detailed data on concentrations of PAH's in soil and vegetation are pre-

ɜnted in Table 2. For brevity, concentration data from apers that included PAH's other than just BaP were ımmed. The BaP was treated separately, because many f the papers addressed BaP only. A number of tentave conclusions can be drawn from the data presented. 'hey are:

1) vegetation and soil near known PAH sources are more highly contaminated with PAH's than their distant counterparts,
2) concentrations of PAH's are generally greater on plant surfaces, such as peelings of fruit, than those in internal tissues,
3) concentrations of PAH's in aboveground plant parts are generally greater than those in belowground plant parts,
4) plants with broad leaves contain more PAH's than plants with narrow leaves, indicating a possible correlation between leaf surface area and direct absorption from the atmosphere,
5) most PAH contamination of vegetation is by direct deposition from the atmosphere, and
6) washing with water is not a very effective method for removing PAH's from contaminated vegetation.

UPTAKE, TRANSLOCATION, AND METABOLISM IN VEGETATION

Relatively few experiments were conducted that address questions relating to the uptake and translocation of PAH's in vegetation. Graf and Nowak (1966) demonstrated growth stimulation of tobacco, rye, and radishes by a number of PAH's, including BaP, and concluded that the compounds were assimilated through the roots. Gunther et al. (1967) found no translocation of several PAH's from orange rind (point of application) to other plant parts; Harms (1975) reported negligible translocation of ^{14}C-BaP from wheat roots to shoots. Durmishidze et al. (1974), using ^{14}C-labeled PAH's, showed translocation from leaves to roots, as well as from roots to upper plant parts in ryegrass, chickpea, alfalfa, cucumber, and vetch. While some plants such as ryegrass translocated PAH's from roots to leaves more readily than from leaves to roots, the opposite was true for other plants such as cucumber. Edwards et al. (1982) demonstrated the uptake of ^{14}C-anthracene from nutrient solution into soybean roots and translocation to leaves, and uptake from air into leaves and translocation to roots. However, Ellwardt (1977) concluded from field experiments with fresh

Table 2—Polycyclic aromatic hydrocarbon (PAH) concentrations in soils and vegetation in various terrestrial habitats of the world.

			PAH concentration				
ɔuntry	Location	Compounds‡	Soil	Vegetation	Plant	Notes	References
			μg/kg†				
orway	Vicinity of a gas works facility	PAH		12 300	Chrysanthemum	Anthracene, pyrene, and fluoronthrene were identified in the PAH extract.	Guddal (1959)
		BaP		3	Tobacco—air cured	The authors concluded that the PAH's formed during smoking make the major contribution to the amounts of PAH's inhaled.	Campbell & & Lindsey (1956)
		Σ6 PAH's		258	Tobacco—air cured		
		BaP		–§	Tobacco—fresh leaves		
		Σ6 PAH's		16	Tobacco—fresh leaves		
		BaP		5	Tobacco—pipe (light)		
		Σ6 PAH's		329	Tobacco—pipe (light)		
		BaP		54	Tobacco—pipe (dark)		
		Σ6 PAH's		1 604	Tobacco—pipe (dark)		
		BaP		30	Tobacco—pipe (herbal)		
		Σ6 PAH's		301	Tobacco—pipe (herbal)		
nited States	Oak forest in Mass.	BaP	40			The author suggests that the occurrence of such concentrations in rural areas distant from major highways and cities cannot be ascribed to air pollution.	Blumer (1961)
	Pine forest in Mass.	BaP	40				
	Mixed forest in Mass.	BaP	1 300				
	Mixed forest in Conn.	BaP	240				
	Garden soil in Conn.	BaP	90				
	Plowed field in Conn.	BaP	900				
ɜrmany	Beech forest near Lake Constance	BaP	1.5				Bornell & Kunte (1964)
		Σ3 PAH's	36.5				
	Beech forest near Darmstadt (pop. 100 000+)	BaP	4.0				
		Σ3 PAH's	184.0				
	Spruce forest near Lake Constance	BaP	1.5				
		Σ3 PAH's	46.5				
	Oak forest near Darmstadt	BaP	1.5				
		Σ3 PAH's	71.5				
	Mixed forest near Lake Constance	BaP	2.5				
		Σ3 PAH's	47.5				
	Mixed forest near Darmstadt	BaP	2.5				
		Σ3 PAH's	42.5				
	Far from industry	BaP		0.126	Wheat seeds		Boling (1964)
	Far from industry	BaP		0.163	Rye seeds		

(continued on next page)

Table 2—Continued.

Country	Location	Compounds‡	PAH concentration Soil	PAH concentration Vegetation	Plant	Notes	References
			μg/kg†				
	Far from industry	BaP		0.063	Oat seeds		
	Far from industry	BaP		0.115	Barley seeds		
	Near industry	BaP		0.470	Wheat seeds		
	Near industry	BaP		0.699	Rye seeds		
	Near industry	BaP		0.360	Oat seeds		
	Near industry	BaP		1.210	Barley seeds		
Switzerland	Timber line of the Wetterstein Mountains (far from industry)	BaP		16	Green beech leaves	The authors attributed these concentration to endogenous synthesis.	Graf & Diehl (1966)
		Σ6 PAH's		494	Green beech leaves		
		BaP		66	Yellow beech leaves		
		Σ6 PAH's		2 230	Yellow beech leaves		
		BaP		8	Green oak leaves		
		Σ6 PAH's		256	Green oak leaves		
		BaP		42	Yellow oak leaves		
		Σ6 PAH's		1 324	Yellow oak leaves		
		BaP		12	Green tobacco leaves		
		Σ6 PAH's		468	Green tobacco leaves		
		BaP		38	Yellow tobacco leaves		
		Σ6 PAH's		916	Yellow tobacco leaves		
		BaP		12	Lettuce		
		BaP		20	Spinach		
		BaP		50	Endive		
United States	Near busy highway in Calif.—high air pollution	Anthracene		25 000	Orange rind		Gunther et al. (1967)
	Calif. desert area—low air pollution	Anthracene		0	Orange rind		
County and location not given		BaP		4	Palm kernel oil	Much higher concentrations were found in coconut oil samples from smoke-dryed copra.	Grimmer & Hildebrandt
		Σ13 PAH's		180	Palm kernel oil		
		BaP		11	Sunflower oil		
		Σ13 PAH's		123	Sunflower oil		
		BaP		1	Linseed oil		
		Σ13 PAH's		78	Linseed oil		
		BaP		3	Rapeseed oil		
		Σ13 PAH's		56	Rapeseed oil		
		BaP		1	Cottonseed oil		
United States		Σ13 PAH's		41	Cottonseed oil		
		BaP		1	Cocoa butter		
		Σ13 PAH's		39	Cocoa butter		
		BaP		2	Groundnut oil		
		Σ13 PAH's		39	Groundnut oil		
		BaP		2	Soybean oil		
		Σ13 PAH's		35	Soybean oil		
		BaP		1	Palm oil		
		Σ13 PAH's		4	Palm oil		
Russia	Soil near oil refinery	BaP	200 000			In areas where shale tar was applied, BaP was degraded rapidly by soil microflora in the soil after plowing.	Shabad et al. (1971)
	Remote area—high soddy podzolic soil	BaP	0.67–0.80				
	Remote area—medium soddy podzolic soil	BaP	2.40–3.00				
	Remote area—soddy carbonate soil	BaP	11.30–12.60				
	Plowed cotton field (avg to 30 cm depth)	BaP	4.6			Suggested an endogenous "background" level of BaP in the soil of 1–3 μg/kg and never exceeding 10 μg/kg.	
	Plowed cotton field treated with shale tar (1.5 Mg/ha)	BaP	13.1				
	Wheat field-control (avg to 30 cm depth)	BaP	0.4				
	Wheat fields treated with shale tar (1.5 Mg/ha)	BaP	68.0				
	Forest near Moscow	BaP	51.4–66.8				
Germany	Far from industry	BaP		0.73	"Grain"		Fritz (1971)
	Near industry	BaP		2.20	"Grain"		
	500–100 m from lignite plant	BaP	1 100–4 000				
	400–100 m from lignite plant	BaP	10 000				
	500 m from tar plant	BaP	120 000				
	1000 m from soot (?) plant	BaP	800				
	500 m from soot (?) plant	BaP	1 000				
	100 m from soot (?) plant	BaP	3 000				
	< 10 m from soot (?) plant	BaP	650 000				
	Suburbs of city	BaP		0.2–0.5	Apple peels		
	Industrial area	BaP		30–60	Apple peels		
	Suburbs of city	BaP		0.1–0.4	Apple interior		

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Table 2—Continued.

Country	Location	Compounds‡	PAH concentration Soil	Vegetation	Plant	Notes	References
			μg/kg†				
	Industrial area	BaP		5-6	Apple interior		
	Suburbs of city	BaP		23	Lettuce		
	Industrial area	BaP		150	Lettuce		
Russia	Near airport runway	BaP	6.3-41.8	2.1-26.7		Concentrations were 8-9 times greater than at a more distant control site.	Audere et al. (1973)
Russia (Moscow)	Area near high BaP exhaust	BaP	191 000.0			Author concludes from the data that BaP is relatively stable and accumulates in soil. BaP content in vegetation was dependent on distance from the source.	Shabad (1968)
	District of old buildings	BaP	346.5				
	Another old district	BaP	268.5				
	District of new buildings	BaP	104.5				
	Settlement close to Moscow	BaP	81.4				
	Field near heavy auto traffic	BaP	79.3				
	Zone near Kljasma water reservoir	BaP	0				
	Within 300 m of BaP source (factories)	BaP		600-5 900	Unwashed vegetation		
	Within 300 m of BaP source (factories)	BaP		600-5 900	Unwashed vegetation		
Yugoslavia	Soil close to source	BaP	900	40.5	Sunflower oil		Stevcevska & Jovanovic-Kolar (1974)
		BaP	900	16.2	Sunflower oil		
		BaP	747	38.9	Sunflower oil		
		BaP	747	11.5	Sunflower oil		
		BaP	168	18.2	Sunflower oil		
		BaP	168	7.2	Sunflower oil		
	Soil 10 km away from source	BaP	251	23.1	Sunflower oil		
		BaP	251	9.2	Sunflower oil		
	Soil 20 km away from source	BaP	29	0.8	Sunflower oil		
		BaP	29	0.2	Sunflower oil		
Czechoslovakia	Blansky forest soil	BaP	8.3-16.5			Data indicate the source of contamination is from the air. Amount of contamination was proportional to the length of growing season and to surface texture. For example, values were very high for leafy parsley and low for smooth tomato fruit.	Kolar et al. (1975)
	Urban/industrial area soil	BaP	37.7-42.1	24.3	Parsley tops		
		BaP	37.7-42.1	5.1	Corn—aboveground		
		BaP	37.7-42.1	6.2	Spinach		
		BaP	37.7-42.1	8.6	Lettuce		
		BaP	37.7-42.1	20.9	White cabbage		
		BaP	37.7-42.1	7.5	Red clover		
		BaP	37.7-42.1	0.2	Oats—grain		
		BaP	37.7-42.1	4.6	Oats—aboveground	Washing vegetables in cold water removes a maximum of 25% of the contamination and generally much less.	Kolar et al. (1975)
		BaP	37.7-42.1	0.1	Wheat—grain		
		BaP	37.7-42.1	4.6	Wheat—aboveground		
		BaP	37.7-42.1	0.3	Barley—grain		
		BaP	37.7-42.1	4.5	Barley—aboveground		
	Urban industrial area soil	BaP	37.7-42.1	5.3	Radish—tops		
		BaP	37.7-42.1	1.2	Radish—roots		
		BaP	37.7-42.1	0.2	Potato—tuber		
		BaP	37.7-42.1	0.1	Tomato—fruit		
		BaP	37.7-42.1	12.3	Cabbage		
United States	Coniferous forest soil in Maine	PAH's	7 000			Authors suggest that much of the PAH's found in soil and sediments originated from forest and prairie fires.	Youngblood & Blumer (1975)
	Oak forest in Mass.	PAH's	13 000				
	Soil near Air Force base	PAH's	2 000				
Switzerland	Soil from town near highway	PAH's	21 000-300 000			Data suggest internal combustion engines as the major source in the areas sampled. Concentrations in the alpine soils represent background levels.	Blumer et al. (1977)
	Soil from open country near town	PAH's	5 000-120 000				
	Alpine soils (850- to 600-m elevation)	PAH's	4 000-8 000				
Finland	Villages in forested areas	Σ10 PAH's		trace	Lettuce	Data suggest that concentrations of PAH's in vegetation vary with distance from industrial smokestacks, heavy traffic, and residential heating units.	Pyysalo (1979)
	Villages in South and Central Finland	Σ10 PAH's		0	Lettuce		
		Σ10 PAH's		3	Lettuce		
	Villages in South Finland (no industry)	Σ10 PAH's		18	Cabbage		
	Suburb, 2 km from industrial area	Σ10 PAH's		0-102	Cabbage		
		Σ10 PAH's		15-69	Celery Cabbage		
	City with chemical industry —10 km from international airport; 1 km from industrial	Σ10 PAH's		35-46	Parsley	All values are given in μg/kg *fresh* wt.	
		Σ10 PAH's		12-78	Cabbage		
		Σ10 PAH's		1-44	Celery cabbage		
		Σ10 PAH's		0-17	Veg. in greenhouse		

(continued on next page)

Table 2—Continued.

Country	Location	Compounds‡	PAH concentration Soil	PAH concentration Vegetation	Plant	Notes	References
			μg/kg†				
	Downtown Helsinki	Σ10 PAH's		86	Lettuce		
	Suburbs of Helsinki						
	(10 km west)	Σ10 PAH's		19	Lettuce		
	(20 km north)	Σ10 PAH's		8	Lettuce		
	Suburbs of cities in:						
	eastern Finland	Σ10 PAH's		61	Lettuce		
	southern Finland	Σ10 PAH's		5	Lettuce		
Russia	1 km NE of plastic factory	BaP	5.8-299.7	4.62	Potato tubers	Benzanthracene and dibenzanthracene were also detected in the vegetation. The generally higher concentractions in the cabbage was attributed to the branching root system and spreading leaves of cabbage.	Shkodich & Litvinov (1979)
		BaP	5.8-299.7	10.81	Cabbage leaves		
	5 km NE of above	BaP	5.8-299.7	1.88	Potato tubers		
	5 km NE of above	BaP	5.8-299.7	2.62	Cabbage leaves		
	2 km SW of chemical factory	BaP	5.8-299.7	23.49	Potato tubers		
		BaP	5.8-299.7	14.00	Cabbage leaves		
	3 km SW of above	BaP	5.8-299.7	5.38	Potato tubers		
	3 km SW of above	BaP	5.8-299.7	9.87	Cabbage leaves		
	4 km SW of above	BaP	5.8-299.7	4.37	Potato tubers		
	4 km SW of above	BaP	5.8-299.7		Cabbage leaves		
	5 km SW of above	BaP	5.8-299.7	2.06	Potato tubers		
	5 km SW of above	BaP	5.8-299.7	0.0	Cabbage leaves		
	1 km NE of above	BaP	5.8-299.7	10.12	Potato tubers		
	1 km NE of above	BaP	5.8-299.7	9.70	Cabbage leaves		
	Control (agric. district)	BaP	§	0.15	Potato tubers		
		BaP	§	0.17	Cabbage leaves		
Poland	Plants from marketplace	BaP		0-2.16	White cabbage		Sokolowska (1980)
	Field remote from traffic & industry	BaP		0.29-0.59	White cabbage		
	Near high traffic—remote from industry	BaP		0.24-0.54	White cabbage		
	Near electric power plant (300-1000 m)	BaP		0.69-1.97	White cabbage		
Sweden	8-15 m from highway	BaP		1.0	Lettuce	Concentrations in plants are dependent on distance from source and meteorological conditions.	Larsson & Sahlberg (1981)
		Σ15 PAH's		50.0	Lettuce		
	15-50 m from highway	BaP		0.4	Lettuce		
		Σ15 PAH's		26.0	Lettuce		
	150-800 m from airport	BaP		0.5	Lettuce		
		Σ15 PAH's		24.0	Lettuce		
	0.5-1.5 m from Al smelter	BaP		12.4	Lettuce		
		Σ15 PAH's		654.0	Lettuce		
	2.0-6.5 m from above	BaP		1.3	Lettuce		
		Σ15 PAH's		128.0	Lettuce		
	Industrial area	BaP		0.1	Lettuce		
		Σ15 PAH's		13.0	Lettuce		
	Urban residence area	BaP		0.2	Lettuce		
		Σ15 PAH's		13.0	Lettuce		
		BaP		0.1	Lettuce		
		Σ15 PAH's		12.0	Lettuce		
Norway	Avg from 3 locations	Σ10 PAH's		43.5	Kale	Data indicate concentrations in vegetables depend on distance from source. Kale generally has a higher concentration of PAH's because of its longer growing period and greater adsorption capacity.	Kveseth et al. (1981)
	Avg from 6 locations	Σ16 PAH's		16.4	Lettuce		
	Avg from 2 locations	BaP		0.2	Lettuce		
	5 m from highway (8 locations)	Σ30 PAH's		47.0	Lettuce		
	5 m from highway (7 locations)	BaP		0.2	Lettuce		
	10 m from highway (3 locations)	Σ30 PAH's		15.7	Lettuce		
Canada	Cultivated soil (surface, 5- and 15-cm depths averaged)—50 m south of one of Canada's busiest highway—Hwy 401 in Toronto.	BaP	86.6	7.36	Onion peel (mature)	Vegetables with smaller contacting surface areas contained less PAH's. Low molecular weight PAH's were absorbed by vegetables more readily than high molecular weight compounds. Authors concluded that vegetables grown in PAH-polluted areas do not contribute significantly to the total PAH intake if they are thoroughly washed and peeled.	Wang & Meresz (1981)
		Σ17 PAH's	1 109.3	202.70	Onion peel (mature)		
		BaP	86.6	0.06	Peeled onion (mature)		
		Σ17 PAH's	1 109.3	3.64	Peeled onion (mature)		
		BaP	86.6	0.03	Onion peel (fresh)		
		Σ17 PAH's	1 109.3	1.86	Onion peel (fresh)		
		BaP	86.6	0.01	Peeled onion (fresh)		
		BaP	86.6	0.21	Beet peel		
		Σ17 PAH's	1 109.3	15.16	Beet peel		
		BaP	86.6	0.02	Beet without peel		
		Σ17 PAH's	1 109.3	1.24	Beet without peel		
		BaP	86.6	0.01	Tomato peel		
		Σ17 PAH's	1 109.3	0.95	Tomato peel		

† Values are per gram dry wt except where noted under "Notes."
‡ BaP = benzo(a)pyrene. Σ(no.)PAH's—Concentrations of each of a given number of individual PAH's were summed.
§ -- Not determined.

compost containing a number of PAH's and with several agricultural crops that little or no uptake by plant roots occurred.

The rate (amount/unit time) of PAH uptake by plants is dependent on a number of factors, including PAH concentration and plant species. Deubert et al. (1979) found that corn and 'Mericopa' wheat seeds absorbed BaP in proportion to BaP concentrations in water used for soaking the seeds. Even though seeds were not washed before analysis, it was concluded that actual uptake had occurred because of growth stimulation of seedling roots. Edwards et al. (1982) reported that ^{14}C-anthracene uptake by soybeans from nutrient solution was directly proportional to anthracene concentration in the solution. Field collections of vegetation growing in PAH-contaminated environments (Audere et al., 1973; Stevcevska & Jovanovic-Kolar, 1974; Wang & Meresz, 1981) lend support to laboratory studies that relate uptake rates to concentrations in the environment. Studies that showed differences in assimilation rates with different plant species include those by Shabad and Cohan (1972), Shabad et al. (1971), Durmishidze (1977), and Linne and Martens (1978). However, Shabad and Cohan (1972) attributed some of the differences in PAH concentrations to different rates of catabolism rather than to different rates of assimilation.

Other factors that affect PAH uptake rates by plants include the nature of the substrate in which the plant is growing, PAH solubility, PAH phase (vapor or particulate), and molecular weight. Dorr (1970) found no uptake of BaP by wheat and rye from nutrient solution nor soil when BaP was applied in insoluble form. However, uptake and translocation did occur when BaP was dissolved in oil before applying to the substrate. Muller (1976) reported greater uptake of ^{14}C-BaP by carrots, radishes, and spinach growing in sand culture when the ^{14}C-BaP was applied dissolved in benzene than when dissolved in plant oil or detergent, and greater uptake of BaP by carrots and radishes growing in sand than in soil and compost. Dorr (1970) found greater uptake of BaP by rye from nutrient solution than from soil, but reported no effect of different soil types on uptake rates. Edwards et al. (1982) observed more uptake of ^{14}C-anthracene by soybeans from nutrient solution than from soil. Larsson and Sahlberg (1981) suggested that, based on removal by washing, lower molecular-weight PAH's in the vapor phase were more readily taken up by lettuee leaves than were larger, particle-bound PAH's. Wang and Meresz (1981) reported PAH profiles from vegetation harvested near known PAH sources that indicated lower molecular weight PAH's were absorbed more readily than higher molecular weight PAH's.

Polycyclic aromatic hydrocarbons may concentrate more in some plant tissues than in others. Wagner and Siddiqi (1970), Shabad and Cohan (1972), and Stevcevska and Jovanovic-Kolar (1974) reported higher concentrations of BaP in the vegetative portion of wheat than in wheat seeds of plants growing in substrates containing BaP. Siegfried (1975) found more BaP in carrot and lettuce tops than in roots of plants growing in soil containing BaP. Muller (1976) found that most of the BaP taken up by carrots growing in sand, to which BaP had been added, remained associated with the roots after 123 d of exposure. Conversely, Linne and Martens (1978) reported more PAH (a total of 11 PAH's including BaP) in the foliage of carrots than in the roots after 150 d of growth in various soil compost mixtures containing PAH's.

While relatively little is known about PAH uptake and translocation in terrestrial plants, even less is known about the chemical fate of these compounds within plants. Dorr (1970) found a decline in BaP concentrations in rye plants after 30 d of growth following a period (20 d) of increasing concentrations due to uptake from nutrient solution and soil. The decline in BaP concentration was attributed to degradation or chemical changes in the BaP within the plants. Durmishidze et al. (1974), using ^{14}C-BaP, demonstrated chemical transformations of BaP (mostly to organic acids) within a number of different plant species. Durmishidze (1977) reported similar results with both BaP and benz(a)-anthracene. The amount of BaP catabolized over a 14-d period varied from 2 to 18% of the BaP assimilated and depended upon plant species. Using ^{14}C-anthracene, Edwards et al. (1982) demonstrated the catabolism of anthracene by soybeans through changes in percentages of chromatographed compounds and small amounts of $^{14}CO_2$ efflux from the plants. Trenck and Sandermann (1978, 1980) reported the metabolism of BaP by microsomal fractions of parsley and soybeans in cell suspension cultures. They found the metabolites to be different from those formed by mammal microsomal fractions.

More detailed information on uptake of PAH's by terrestrial vegetation is given in Table 3. From these data and the research discussed above, a number of tentative conclusions can be listed:

1) some terrestrial plants can take up PAH's through their roots and/or leaves and translocate them to various plant parts,
2) uptake rates are dependent on PAH concentrations, solubility, phase (vapor or particulate), molecular size, support media anchoring the plants, and plant species,
3) PAH's may concentrate in certain plant parts more than in other parts, and
4) some PAH's can be catabolized by plants.

The conclusions listed above reflect the results from relatively few controlled experiments. Conclusions vary widely between experiments and, although much more research is needed, a concensus would suggest that PAH's can enter the food chain by contamination of vegetation. The seriousness of this problem depends in part on molecular species and contamination levels and in part on degradation rates and degradation products in air, soil, and vegetation.

DEGRADATION OF PAH's IN THE ENVIRONMENT

Degradation (chemical modification) of PAH's is not thoroughly reviewed here, but a few papers dealing with photo-oxidation and degradation by microorganisms

Table 3—Uptake of polycyclic aromatic hydrocarbon (PAH's) by vegetation.

Plant	Growth medium	Growth period	Compound‡	PAH concentration Source	PAH concentration Vegetation	Notes	References
		days		μg/kg†			
Orange rind	Soil (see Notes)	50	Anthracene	1 000	≈ 100	PAH was applied dissolved in methylene chloride solution to give concentrations in the rind that are shown (source). PAH's accumulated in the rind oil but not in the pulp. The PAH's degraded (mostly by photo-oxidation) rapidly the first 5–10 d after application and then appeared to stabilize in the rind, except for dibenzo[a,i]pyrene, which was still degrading 50 d after application.	Gunther et al. (1967)
Orange rind	Soil (see Notes)	50	3-Methylchlor-anthrene	10 000	≈ 50		
Orange rind	Soil (see Notes)	50		10 000	≈ 50		
Orange rind	Soil (see Notes)	50	Dibenz[a,h]-anthracene	10 000	≈ 1 000		
Orange rind	Soil (see Notes)	50	Benzo[a]pyrene	10 000	≈ 100		
Orange rind	Soil (see Notes)	50	Dibenzo[a,i]-pyrene	10 000	≈ 100		
Rye (tops only)	Nutrient solution	20	BaP	167	2 760	The amount of BaP absorbed by plants during the 20-d growth period from nutrient solution correlated well with concentration in the solution. The reduced concentration in vegetation after 30 d of growth indicated degradation and/or metabolic changes of BaP by the plants. Uptake rates from soil did not depend on soil type.	Dorr (1970)
(tops only)	Nutrient solution	20	BaP	837	4 240		
(tops only)	Nutrient solution	10	BaP	1 670	5 250		
(tops only)	Nutrient solution	20	BaP	1 670	9 140		
(tops only)	Nutrient solution	30	BaP	1 670	2 550		
(tops only)	Soil-rich organic sandy loam	6	BaP	3 333	0		
(tops only)	Soil-heavy loess	6	BaP	3 333	0		
(tops only)	Soil-rich organic sandy loam	30	BaP	3 333	200		
(tops only)	Soil-heavy loess	30	BaP	3 333	130		
Wheat shoots	Soil	To maturity	BaP	Control	15		Wagner & Siddiqi (1970)
Wheat shoots	Soil	To maturity	BaP	1 mg/vessel	24		
Wheat shoots	Soil	To maturity	BaP	10 mg/vessel	24		
Wheat straw	Soil	To maturity	BaP	Control	7		
Wheat straw	Soil	To maturity	BaP	10 mg/vessel	8		
Wheat grain	Soil	To maturity	BaP	Control	3		
Wheat grain	Soil	To maturity	BaP	10 mg/vessel	3		
Wheat shorts	Soil	To maturity	3,4 benzofluor-anthen	Control	100		
Wheat shorts	Soil	To maturity	3,4 benzofluor-anthen	1 mg/vessel	237		
Wheat shorts	Soil	To maturity	3,4 benzofluor-anthen	10 mg/vessel	223		
Wheat straw	Soil	To maturity	3,4 benzofluor-anthen	Control	104		
Wheat straw	Soil	To maturity	3,4 benzofluor-anthen	10 mg/vessel	220		
Wheat grain	Soil	To maturity	3,4 benzofluor-anthen	Control	76		
Wheat grain	Soil	To maturity	3,4 benzofluor-anthen	10 mg/vessel	98		
Aster and nasturtium	Soil	No data	BaP	150	9	Plants were grown under controlled conditions. Uptake was assumed to be from the soil.	Shabad et al. (1971)
	Soil	Several weeks	BaP	7 000	57		
Cottonseed oil	Soil (control)	Maturity	BaP	4–8	0.9–2.4	Nerosin, a soil conditioner, developed from shale oil and containing BaP and other PAH's, was applied to the soil.	Shabad & Cohan (1972)
Cottonseed oil	Soil (treated)	Maturity	BaP	up to 100	0.9–2.4		
Maize seeds	Soil (control)	Maturity	BaP	3–7	0.08–0.15		
Maize seeds oil	Soil (control)	Maturity	BaP	3–7	1.6–3.0		
Maize seeds	Soil (treated)	Maturity	BaP	20–30	0.08–0.15		
Maize seeds oil	Soil (treated)	Maturity	BaP	20–30	1.6–3.0		
Sunflower seed	Soil (control)	Maturity	BaP	3–7	0.47		
Sunflower seed oil	Soil (control)	Maturity	BaP	3–7			
Sunflower seed	Soil (treated)	Maturity	BaP	20–30	0.66–2.10		
Sunflower seed oil	Soil (treated)	Maturity	BaP	20–30	1.32–4.20		
Wheat (S-29)	Soil (control)	Maturity	BaP	0.1–3.0	0.44		
Wheat (S-29)	Soil (treated)	Maturity	BaP	170	0.22		
Wheat (S-29) seed	Soil (control)	Maturity	BaP	0.1–3.0	0.29		
Wheat (S-29) seed	Soil (treated)	Maturity	BaP	170	0.38		
Wheat (S-29) straw	Soil (control)	Maturity	BaP	0.1–3.0	4.52		
Wheat (S-29) straw	Soil (treated)	Maturity	BaP	170	3.60		
Wheat (E-841) seed	Soil (control)	Maturity	BaP	0.1–3.0	0.84		
Wheat (E-841) seed	Soil (treated)	Maturity	BaP	170	0.92		
Wheat (E-841) straw	Soil (control)	Maturity	BaP	0.1–3.0	27.0		
Wheat (E-841) straw	Soil (treated)	Maturity	BaP	170	26.7		
Potatoes	Soil (control)	Maturity	BaP	0.1–3.0	0.08–0.22		
Potatoes	Soil (treated)	Maturity	BaP	10–30	0.11–29.4		
Carrot roots	Soil (control)	80	BaP	85	0.08–0.14	Carrot roots were washed before analysis. Carrot tops were not washed.	Siegfried (1975)
Carrot roots	Soil and compost	80	BaP	130	0.13–0.19		
Carrot roots	Soil and compost	80	BaP	185	0.07–0.08		
Carrot tops	Soil and compost	80	BaP	85–185	1.1–4.3		
Head lettuce	Soil and compost	80	BaP	85–185	0.2–1.3		

(continued on next page)

Table 3—Continued.

Plant	Growth medium	Growth period	Compound‡	PAH concentration: Source	PAH concentration: Vegetation	Notes	References
		days		μg/kg†			
Carrot roots	Quartz sand	123	BaP	75	20	^{14}C-BaP tracer dissolved in benzene was applied to growth medium. Reduced uptake was observed in experiments with quartz sand if plant oil or detergent were used as solvents. BaP was mainly incorporated in the cortical region of carrots and radish. Authors suggest only a slight increase in BaP content of food plants grown in composted solid town waste. Uptake was strongly dependent upon the chemical composition and physical nature of the substrate. Values given were taken from graphs and are therefore only close approximations.	Muller (1976)
Carrot roots	Quartz sand	123	BaP	150	180		
Carrot roots	Quartz sand	123	BaP	750	290		
Carrot roots	Quartz sand	123	BaP	1 500	300		
Carrot roots	Quartz sand	123	BaP	75			
Carrot roots	Quartz sand	123	BaP	150			
Carrot roots	Quartz sand	123	BaP	750	10		
Carrot roots	Quartz sand	123	BaP	1 500	18		
Carrot roots	Quartz sand	123	BaP	3 500	40		
Carrot roots	Composted town waste & soil	123	BaP	750	10		
Carrot roots		123	BaP	1 500	25		
Carrot roots		123	BaP	3 500	60		
Carrot roots		123	BaP	750	5		
Carrot roots		123	BaP	1 500	10		
Carrot roots		123	BaP	3 500	20		
Radish tubers	Quartz sand	49	BaP	150	<10		
Radish tubers	Quartz sand	49	BaP	900	15		
Radish tubers	Quartz sand	49	BaP	3 500	45		
Radish leaves	Quartz sand	49	BaP	150	<10		
Radish leaves	Quartz sand	49	BaP	900	15		
Radish leaves	Quartz sand	49	BaP	3 500	85		
Radish tubers	Composted town waste & soil	49	BaP	150	<10		
Radish tubers		49	BaP	900	<10		
Radish tubers		49	BaP	3 500	<10		
Radish leaves		49	BaP	150	<10		
Radish leaves		49	BaP	900	15		
Radish leaves		49	BaP	3 500	20		
Potato tubers	Soil treated with fresh compost (100 Mg/ha)	No data	PAH's†	429	27	Author suggests that because plants with a large leaf surface (potato) have a higher amount of PAH's than plants with a smaller leaf surface (oat and rye), PAH's contamination may be from the atmosphere. This is supported by the fact the potato haulms were more contaminated with PAH's than tubers.	Ellwardt (1977)
Potato haulms			PAH's†	429	111		
Oat grain			PAH's†	429	96		
Oat straw			PAH's†	429	82		
Rye grain			PAH's†	429	25		
Rye straw			PAH's†	429	32		
Potato haulms	Soil treated with decomposed compost (100 Mg/ha)	No data	PAH's†	432	31		
Potato haulms			PAH's†	432	125		
Oat grain			PAH's†	432	51		
Oat straw			PAH's†	432	78		
Rye grain			PAH's†	432	33		
Rye straw			PAH's†	432	28		
Potato tubers	Test plot—no compost	No data	PAH's†	257	19		
Potato haulms			PAH's†	257	104		
Oat grain			PAH's†	257	48		
Oat straw			PAH's†	257	33		
Rye grain			PAH's†	257	26		
Rye straw			PAH's†	257	27		
Green bean—leaves	Nutrient solution	To maturity	BaP	4	7	It was concluded that BaP did not translocate nor concentrate in the crops tested. [^{14}C] BaP was used and the small amount of activity in bean leaves and cottonseeds was not found to be BaP. The activity found was attributed to degradation, volatilization, and deposition onto the plant cuticle.	Blum & Swarbrick (1977)
Green beans—stems		To maturity	BaP	4	0		
Green bean—seeds		To maturity	BaP	4	2		
Cantaloupe—fruit		To maturity	BaP	4	0		
Cotton		To maturity	BaP	4	0		
Carrot roots	Composted municipal waste mixed with sand (25/75)	150	BaP	1 430	8.5	Mushroom fruiting bodies grown in the same substrates as the carrots contained no detectable amount of PAH's. Compost used in these experiments contained concentra-	Linne & Martens (1978)
Carrot foliage		150	BaP	1 430	9.0		
Carrot roots		150	PAH's‡	22 140	138.0		
Carrot foliage		150	PAH's‡	22 140	143.0		
Carrot roots	Garden soil mixed with						

Table 3--Continued.

Plant	Growth medium	Growth period	Compound‡	PAH concentration Source	PAH concentration Vegetation	Notes	References
		days		μg/kg†			
Carrot foliage		150	PAH's‡	72.5	66.8		
Corn seeds	Vermiculite (see Notes)	0.25	BaP	0.5	210 000	Seeds were soaked in water	Deubert
Corn seeds		0.25	BaP	1.0	430 000	containing BaP at concentra-	et al.
Corn seeds		0.25	BaP	5.0	2 250 000	tions indicated. The seeds	(1979)
Corn seeds		0.25	BaP	0.0	4 290 000	were then transferred to	
Corn seeds		0.25	BaP	20.0	8 570 000	vermiculite for germination.	
Corn seeds		0.50	BaP	0.5	440 000	Seeds were not washed before	
Corn seeds		0.50	BaP	1.0	880 000	analysis for BaP. Corn root	
Corn seeds		0.50	BaP	5.0	6 250 000	growth was stimulated at the	
Corn seeds		0.50	BaP	10.0	8 830 000	lowest BaP concentrations	
Corn seeds		0.50	BaP	10.0	17 650 000	and to a lesser extent at the	
Wheat seeds		0.25	BaP	0.5	140 000	higher concentrations. Wheat	
Wheat seeds		0.25	BaP	1.0	280 000	was not as sensitive as corn.	
Wheat seeds		0.25	BaP	5.0	1 440 000	The authors concluded that	
Wheat seeds		0.25	BaP	10.0	2 880 000	BaP does affect plant growth	
Wheat seeds		0.25	BaP	20.0	–	and may be a new type of plant growth regulator.	
Soybean roots	Soil (see Notes)	4	Anthracene	11.1	125	Water containing ^{14}C-	Edwards
Soybean stems		4	Anthracene	11.1	500	anthracene was added	et al.
Soybean leaves		4	Anthracene	11.1	125	to soil.	(1982)

† Includes benzo(a)pyrene and six other PAH's.
‡ Includes BaP plus 11 other PAH's.

are discussed. The National Academy of Sciences (1972) reviewed the literature on PAH reactions in the atmosphere, including photoxidation and those with ozone (O_3). Catabolism in plants was included in the discussion above.

Photo-Chemical Oxidation

Photo-oxidation may be one of the most important processes in the removal of PAH's from the atmosphere (NAS, 1972), yet some of the reaction products may also be carcinogenic, making it risky to evaluate carcinogenicity solely on PAH content (Fox & Olive, 1979). One of the more common photo-oxidation reactions of PAH's is the formation of endoperoxides that ultimately undergo a series of reactions to form quinones (NAS, 1972). Katz et al. (1979) observed that BaP is photo-oxidized to BaP quinones that are direct-acting mutagens. They found the reactions to occur faster than BaP was irradiated in the presence of O_3. Falk et al. (1956) reported the photo-oxidation of PAH's in air, with BaP more readily photo-oxidized than the other PAH's tested. They also reported negligible photo-oxidation when PAH's were adsorbed on soot. Smog, however, acted as a strong oxidizing agent and stimulated PAH degradation. Thomas et al. (1968) found that BaP adsorbed on soot was photo-oxidized more readily than when adsorbed on small beads (presumably a surface area effect). Korfmacher et al. (1980a, 1980b) performed experiments that did not support the widespread belief that particulate association of PAH's will promote their photo-oxidation. They found that BaP, pyrene, and anthracene will photo-oxidize efficiently in liquid solution, but are highly resistant to photo-oxidation when adsorbed on fly ash. They also reported that PAH's adsorbed on fly ash that undergo non-photo-oxidation are generally those containing a single-bonded C atom attached to an aromatic ring. Anthracene and BaP may be exceptions, because they do not contain a "benzylic" C atom, but they nevertheless do exhibit very slow spontaneous oxidation when adsorbed on fly ash. Gunther et al. (1967) attributed the degradation of several PAH's injected into orange rinds partially to photo-oxidation.

Microbial Degradation

Tausson (1950) first demonstrated that several PAH's, including naphthalene, anthracene, and phenanthrene, can serve as substrates for some soil organisms and are "completely" metabolized. Groenewegen and Stolp (1981) isolated microorganisms that can use the compounds mentioned above as their sole C source. However, they could show degradation of some of the less-water-soluble PAH's, such as benz(a)anthracene and BaP, only when the PAH's were mixed with soil, water, and a substance to stimulate growth of oxygenase-active organisms. Shabad et al. (1971) discussed a number of experiments that demonstrated bacterial degradation of BaP in soil. They reported 50–80% destruction of BaP over a period of "several" days by bacteria in soil contaminated with shale oil containing high concentrations (up to 20 000 μg/kg) of BaP. Shabad et al. also found that the capacity of bacteria to degrade BaP increased with BaP content in the soil and that microflora of soil contaminated with BaP were more active in metabolizing BaP than those in "clean" soil. Cerniglia and Crow (1981) demonstrated the metabolism of napthalene, biphenyl, and BaP by a number of different species of yeast, some of which were previously reported in high numbers in oil-polluted soils. Cerniglia and Gibson (1979) reported the degradation of BaP by a filamentous fungus, and Dodge and Gibson (1980) demonstrated the degradation of benz(a)-anthracene by the same fungal species.

Cerniglia and Gibson (1979) reported that the metabolites formed during the degradation of BaP by a fungus were very similar to those formed during BaP metabolism in mammals. Such metabolites are probably responsible for the carcinogenicity of BaP. However,

Shabad et al. (1971) reported that extracts of a medium containing BaP were less carcinogenic to mice (*Mus* spp.) after microbial degradation than before degradation. A more complete review of earlier research on microbial oxidation of PAH's was presented by Gibson (1972). Biochemical pathways for the degradation of a number of PAH's by soil microorganisms have been proposed by Fernley and Evans (1958), Evans et al. (1965), Gibson et al. (1975), and others.

While it has been shown that PAH's are biodegradable and catabolic pathways for a few have been suggested, much more research is needed in this area. Careful attention should be given to the potential carcinogenicity and mutagenicity of intermediate products formed during their decay. Also, literature on rates of PAH degradation in the terrestrial environment is almost nonexistent.

SYNOPSIS

Naturally occurring PAH's in the terrestrial environment from natural forest fires, volcanic activity, and synthesis by plants and microorganisms make a minor contribution to the PAH content in air, soil, and vegetation of the world. The PAH's emitted from the burning of fossil fuels, refuse burning, and agricultural burning are major contributors (>90% of emissions from all sources) to the PAH pool. The PAH's emitted from automobile exhaust are localized along roadways; those emitted from jet aircraft and power plants may be spread over long distances. Neither automobile nor jet engine exhausts are major contributors to the environmental burden of PAH on a global scale. Waste products from industry and municipalities are contributors to soil PAH's in isolated areas.

Much of the PAH released into the atmosphere eventually reaches the soil by direct deposition or by deposition on vegetation. The PAH's may be adsorbed and/or assimilated by plant leaves before entering the animal food chain. A portion of the PAH adsorbed onto plant leaves is washed off by rain, chemically oxidized to other products, or returned to the soil as the plants decay. The PAH's assimilated by vegetation may be translocated, metabolized, and possibly photo-degraded within the plant. However, in some plants growing in highly contaminated areas, assimilation may exceed metabolism and degradation resulting in an accumulation of PAH's in the plant tissues.

Animals and microorganisms can metabolize PAH's to products that may ultimately be completely degraded. The degradation of most PAH's is not completely understood. Those in the soil may be assimilated by plants, degraded by soil microorganisms, or accumulated to relatively high levels in the soil. High PAH concentrations in soil can lead to increased populations of microorganisms capable of degrading them. Perhaps equally as important to the dynamics of PAH cycling in the environment is the physical state of the PAH (whether in vapor phase or associated with particles such as fly ash). Particles may increase or decrease the susceptibility of PAH's to degradation, depending on the PAH's and particles involved.

These generalizations are based on relatively few experiments primarily dealing with BaP, only one of the carcinogenic PAH's. More research is needed in all areas covered by this review. In particular, more work is needed on vegetation, including assimilation, surface contamination, metabolism, and accumulation. The research needs to be conducted with a variety of PAH's in both field and laboratory experiments.

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APPENDIX

Scientific Names of Plants Mentioned in Text and Tables

Common name	Scientific name
Alfalfa	*Medicago sativa* L.
Apple	*Malus sylvestris* Mill.
Aster	*Aster* spp.
Barley	*Hordeum vulgare* L.
Beech	*Fagus grandifolia* L.
Beet	*Beta vulgaris* L.
Cabbage	*Brassica oleracea* var. *capitata* L.
Cantaloupe	*Cucumbis melo* L.
Carrot	*Daucus carota* Sorte.
Celery cabbage	*Brassica pekinensis* Rupr.
Chickpea	*Cicer arietinum* L.
Chrysanthemum	*Chrysanthemum vulgare* Bernh.
Cocoa	*Theobroma cacao* L.
Corn	*Zea mays* L.
Cotton	*Gossypinum hirsutum* L.
Cucumber	*Cucumis sativus* L.
Endive	*Cichorium endiva* L.
Green bean	*Phaseolus vulgaris* L.
Groundnut	*Apios americana* Medic.
Kale	*Brassica oleracca* L.
Lentil	*Lens culinaris* Medic.
Lettuce	*Lactuca sativa* L.
Linseed (flax)	*Linum* spp.
Maize	*Zea mays* L.
Mushroom	*Agaricum bisporus*
Nasturtium	*Tropaeolum* spp.
Oak	*Quercus* spp.
Oat	*Avena sativa* L.
Onion	*Allium cepa* L.
Orange	*Citrus sinensis* Osbeck.
Palm	*Cocos* spp.
Parsley	*Petroselinum crispum* Nym.
Potato	*Solanum tuberosum* L.
radish	*Raphanus sativus* L.
Rape	*Brassica napus* L.
Red clover	*Trifolium pratense* L.
Rye	*Secale cereale* L.
Ryegrass	*Lolium multiflorum* Lam.
Soybean	*Glycine max* Merr.
Spinach	*Spinacia oleracea*
Spruce	*Picea* spp.
Sunflower	*Helianthus* spp.
Tobacco	*Nicotiana tabacum* L.
Tomato	*Lycopersicon esculentum* Mill.
Vetch	*Vicia faba* L.
Wheat (all authors except Deubert)	*Triticum* spp.
Wheat (as given by Deubert et al., 1979)	*Triticum aestivum* L. 'Mericopa'
White cabbage	*Brassica* spp.

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