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Oils and Rubber from Arid Land Plants

Jack D. Johnson and C. Wiley Hinman

Summary. In this article the economic development potentials of *Cucurbita* species (buffalo gourd and others); *Simmondsia chinensis* (jojoba), *Euphorbia lathyris* (gopher plant), and *Parthenium argentatum* (guayule) are discussed. All of these plants may become important sources of oils or rubber.

Arid land vegetation has the potential to relieve some of the United States' dependency on imported oils and rubber. The development of this vegetation could bring into cultivation new cash crops on lands currently not used for food or fiber production. In this article we discuss the economic development potential of *Cucurbita* species (principally buffalo gourd), *Simmondsia chinensis* (jojoba), *Euphorbia lathyris* (gopher plant), and *Parthenium argentatum* (guayule). All of these plants can be grown on arid lands, that is lands that are semiarid or drier, and they may become important sources of oils or rubber (*1*). Included within our definition of "oils" are many edible products as well as substances that may be useful as cosmetic and lubricant bases, waxes, or chemical feedstocks or fuels.

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Cucurbita

Potential uses of *Cucurbita* species include the production of edible oil and protein by-products from the seed, industrial starch from the roots, and forage from the vines. The species most often discussed are *Cucurbita foetidissima* (buffalo gourd), *C. digitata, C. palmata* (coyote melon), and *C. pepo*, all of which may provide good economic returns. A major effort to domesticate the buffalo gourd and to industrialize its production is being conducted by Bemis *et al.* (*2*) at the University of Arizona, and we report some of this work here.

The plant is perennial, reproduces asexually, grows as a weed in regions of low rainfall, and produces a large crop of seeds rich in oil and protein. The roots may weigh up to 50 kilograms after three or four seasons of growth and consist largely of starch. This starch can be hydrolyzed chemically or enzymatically to glucose (dextrose) that is used as a sweetener in foods and beverages. The vines grow along the ground and because of their protein content [10 to 13 percent (*3*)] and digestibility may have forage value.

The oil of the seed has a high ratio of unsaturated to saturated fatty acids that makes it attractive for possible use in foods prepared for consumption by humans. Linoleic acid, an essential fatty acid in the diet of humans and animals, is present in amounts ranging from 50 to 60 percent. Incorporation of the crude oil into the diet of weanling mice in amounts up to 11 percent of the total diet produced excellent growth with no evidence of deleterious effects (*2*).

The crude oil can be extracted from the seed by a solvent process or by mechanical pressing. The remaining seed meal, which contains about 45 percent protein and 45 percent fiber, may be used in raw form as a component of animal feeds. Studies with rodents show that the protein quality of seed meal from the buffalo gourd is similar to that of soybean and cottonseed meals.

Analysis of whole seeds indicates the presence of 32.9 percent crude protein and 33.0 percent crude fat (*2*). Hoffmann (*4*) obtained a whole-seed cyclohexane extract of 16.5 percent. The cyclohexane extract is indicative of relatively high caloric yield and high hydrocarbon content. With seed yields of up to 3000 kilograms per hectare and an estimated 16 percent hydrocarbon content, about 3.5 barrels of crude oil could be produced per hectare. Thus the buffalo gourd is not particularly promising as a producer of crude oils for hydrocarbon use. However, with 1 hectare of this crop producing 1 ton of vegetable oil and 0.5 ton of protein being produced from the seeds, the potential crop value is $650 per hectare. This is based on a value of $0.55 per kilogram of vegetable oil and $0.20 per kilogram of crude protein. Since an estimated 13.5 tons of crude starch per hectare could be produced every 3 years, the approximate value of the starch

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being $10 per ton, the crude starch would add about $45 annually to the crop value to generate a gross cash income of about $695 per hectare each year. Costs to harvest the fruit and roots, to extract the seed, and to convert the seed and roots into oil, protein, and starch have not been estimated.

Improvements in plant genetics and agronomy can be expected to increase gross cash income, but until additional substantial research and development efforts directed particularly at agronomy, processing, and product development are funded, the buffalo gourd probably will remain an interesting but underutilized plant.

Simmondsia chinensis

The jojoba plant grows naturally as a shrub in the Sonoran Desert of the United States and Mexico. Jojoba seeds contain about 50 percent oil by weight. Jojoba has appeared in the botanical literature since 1821. The earliest records of its uses can be found in correspondence from Eusebio F. Kino to King Phillip V dated 1701. Kino referred to the medicinal value of the fruit of jojoba, as did the Italian Jesuit Clavijera in 1789 who described a medicinal use of jojoba "berries" (*5*).

The oil expressed from jojoba seeds is similar to sperm whale oil. The physical and chemical properties of jojoba oil and of the wax produced by hydrogenating the oil are presented in Tables 1 to 3 (*6*).

Jojoba seeds are harvested entirely from natural stands. Oil expressed from these harvested seeds is being sold in limited quantities for an average price of $14 per kilogram. The oil content of the seeds does not decrease with long-term storage. Jojoba oil is remarkably resistant to bacterial degradation, probably because bacteria cannot cleave and metabolize the long-chain esters it contains, mostly hydrocarbons containing 38 to 44 carbon atoms.

Jojoba oil has potential uses as a fuel, as a chemical feedstock, and, because it does not become rancid, as a replacement for vegetable oils in foods, cosmetics, and hair oil. The oil also can be a source of long-chain alcohols, antifoaming agents, and lubricants. The hydrogenated oil is a hard, white crystalline wax. It has potential uses in preparing floor and automobile waxes, waxing fruit, impregnating paper containers, manufacturing carbon paper, and in making candles that have slow-burning and wilt-resistant qualities (*7*).

Table 1. Chemical and physical properties of jojoba oil. Oil from expeller-pressed jojoba seeds starts to freeze at 10.6°C. It solidifies into a thick paste at 7°C. Frozen oil, allowed to warm up, melts at 7°C. [Adapted from (*6*)]

Freezing point	10.6° to 7.0°C
Melting point	6.8° to 7.0°C
Boiling point at 757 mm under N_2	398°C
Smoke point (AOCS Cc9a-48)*	195°C
Flash point (AOCS Cc9a-48)*	295°C
Fire point	338°C
Heat of fusion	21 calories per gram
Refractive index at 25°C	1.4650
Specific gravity	0.863
Total acids	52 percent
Average molecular weight of wax esters	606

*Smoke and flash points determined according to the offical method, Cc9A-48, of the American Oil Chemists Society.

Maximum yields of jojoba seed in the wild or under cultivation are unknown. Plants 3 to 5 meters in width and 5 to 7 meters in height have been found in the wild that yield 14 to 18 kg of clean dry seeds. Institutional and commercial studies are being conducted to determine optimal row spacing and plant density, male to female ratios, and irrigation and fertilization requirements. Studies of planting methods and pest control in this species are also in progress.

Results from research on jojoba are somewhat preliminary. In fact, in the United States, only the experimental plots of Yermanos (*8*) at the University of California, Riverside, have been in existence long enough to produce plants from which satisfactory data on yields can be obtained. Yermanos reports yields of about 400 kg per hectare from 5-year-old plants. Hogan (*9*) has experimental plantings at several sites in Arizona and reports yields of up to 73 grams of seeds per plant from a few 2.5-year-old plants at Mesa, Arizona. Mexican researchers have reported annual seed yields of 2 kg from some 4-year-old plants in Hermosillo; and at Gilat, Israel, researchers obtained an annual yield of more than 3 kg of seed from a 9-year-old jojoba plant.

Yermanos originally planted jojoba 1.5 meters apart in rows 3 m apart (2200 plants per hectare), but now suggests that about 4400 plants can be grown on 1 hectare, the shrubs being planted 0.75 m apart in rows 3 m apart. Other institutional researchers and commercial operators are spacing plants as close as 23 centimeters in rows ranging from 2.4 to 6.1 m apart. Closer plant spacing and row separation are based on the concept of growing the plants in the form of hedgerows and of using over-the-row equipment for cultivation and harvesting. Larger row separation permits intercropping between the rows to generate a source of income during the first 3 to 5 years required for jojoba plants to produce economically significant seed yields.

One of us (J.D.J.) visited some 50 jojoba plantations in California during March and April 1979. On many of these plantations, which were in a region bounded in the south by San Diego and in the north by Chico, the jojoba shrubs were killed by the severe winter cold of 1978 to 1979 (*10*). Many of the other plantation crops survived the cold and were healthy into the summer of 1979. Although young jojoba seedlings require substantial irrigation during the first few weeks after planting to promote rapid and deep growth of the taproot, their ability to withstand cold weather seems to be increased if the water supply is reduced in late summer. All of the jojoba plants that survived the winter cold of 1978–1979 had been hardened off by early withdrawal of irrigation—some farmers indicated that they had not irri-

Table 2. Gas-chromatographic composition of expeller-pressed jojoba oil. [From (*6*)]

Compound	Percentage	Compound	Percentage	Compound	Percentage
Wax esters		Wax esters		Free acids	
C-33	0.02	C-45	0.03	C-16	0.08
C-34	0.08	C-46	0.86	C-18	0.23
C-35	0.04	C-48	0.16	C-19	0.01
C-36	1.16	C-50	0.06	C-20	0.60
C-37	0.02			C-21	0.03
C-38	6.23	Free alcohols		C-22	0.03
C-39	0.04	C-16	0.01	C-24	0.02
C-40	30.56	C-18	0.04		
C-41	0.10	C-20	0.49	Campesterol	0.05
C-42	49.50	C-22	0.49	Stigmasterol	0.08
C-43	0.06	C-24	0.07	Sitosterol	0.21
C-44	8.12	C-26	0.01	Others	0.52

gated the plants since the end of July 1978. Although not all plant scientists agree that early withdrawal of water and hardening off the plant will assist cold weather survival, we are convinced that such treatment was critical to the survival of the California plants.

In the absence of much experience or of many research data concerning the cultivation of jojoba, many unqualified part-time farmers in the mid-1970's came to believe that the plant was so vigorous that it could be planted anywhere, by anyone, and required almost no attention. Some of them thought that incomes of $25,000 per hectare were likely. Such incomes from jojoba are in fact unrealistic and it is important that accurate data on the cultivation of this crop and the expected economic returns be obtained.

Approximately 1500 ha of commercial jojoba plants exist in California, 700 in Mexico, 400 in Arizona, and lesser amounts in other parts of the United States (Florida, New Mexico, and Texas). Jojoba is also grown commercially in Australia, Israel, Saudi Arabia, Iran, Egypt, Jordan, and Ghana. Without doubt, jojoba will eventually become an important agricultural product of arid lands.

Table 3. Mechanical properties of jojoba oil. Values for viscosity are expressed as Saybolt Universal Seconds, and for hardness, as Brinel hardness number. This value compares favorably with that of carnauba wax, the hardest known wax, with a Brinel hardness number of 2.6. [Adapted from (*6*)]

Property	Value
Viscosity	
Pure jojoba oil	
At 37.8°C	127
At 99°C	48
Sulfurized jojoba oil (9.88 percent sulfur)	
At 37.8°C	3518
At 99°C	491
Hardness	
Hydrogenated jojoba	1.9

Euphorbia lathyris

The gopher plant is one of several arid land plants being studied to determine and maximize its hydrocarbon content. Two factors were considered before the hydrocarbon research program at the University of Arizona was initiated: first was the question of whether hydrocarbon farming was agronomically practical; and second was the question of whether hydrocarbon farming could be economically attractive.

To be agronomically practical on a long-term basis, a plant cultivated to produce hydrocarbons should not occupy lands used for food or fiber production. If competition for land develops between food and nonfood oil crops a competitive price spiral will ensue for both. Calvin (*11*) suggested that the use of *E. lathyris* might avoid these difficulties. Not only does this plant yield a significant amount of hydrocarbons, it probably can be grown with less water than any currently cultivated agricultural crop. The plant's ability to produce hydrocarbons, however, seems to depend on high levels of solar radiation.

The only region in the United States possessing both vast areas of uncultivated land and high solar radiation is the Southwest. The primary reason that the land is untilled, of course, is that most of the region is arid. For example, of Arizona's 30 million hectares only 0.5 million hectares are under cultivation. Figure 1 shows those areas of the United States that receive annually from 15 to 50 cm of rainfall and from 450 to 500 langleys of solar radiation. On the basis of these criteria the best areas for growing such a new crop are easily identifiable.

Euphorbia lathyris grown in California may yield 25 barrels of crude oil per hectare (*11*). This yield was derived from plants grown from wild seed that had not been subjected to genetic or agronomic development. In view of the 2000 percent increase in rubber yield achieved during the past 35 years with *Hevea brasiliensis*, another member of the family Euphorbiaceae, it seems reasonable that through genetic and agronomic development a 260 percent increase in the oil yield of *E. lathyris* can be achieved within a reasonable time to produce some 65 barrels of crude oil per hectare.

The shaded and cross-hatched areas in Fig. 1 represent about 120 million hectares of land. We estimate that 8 to 12 million hectares of this land could be used to grow a crop without irrigation or with only minor amounts of supplemental irrigation. To put 12 million hectares in perspective, in the United States approximately 34 million hectares are used for corn cultivation and 32 million for wheat. In all, approximately 146 million hectares are cultivated. If one assumes an annual yield of 65 barrels of oil per hectare, less than 12 million hectares would be needed to meet 10 percent of the current U.S. petroleum demands. Any energy source that meets even 5 percent of the U.S. petroleum demands is significant.

Calvin (*11*) estimated that the costs of growing *E. lathyris* would be $10 per barrel using current technology and assuming an annual yield of 25 barrels per hectare. Removing the oil from the plant involves drying, grinding, and multiple solvent extraction, all of which is estimated to cost $10 per barrel. Thus the total cost of producing crude oil is estimated to be $20 per barrel. Since this estimate is based on lower than expected oil yields and on a very expensive extraction procedure, we have accepted the figure as a reasonable working estimate of the economic feasibility. It is noteworthy that some world crude oil prices currently exceed $25 per barrel; some are as high as $45 per barrel.

A research program to explore further these possibilities was begun in July 1978. As many desert plants as could be found that contained measurable amounts of hydrocarbons were collected in the field. These plants were analyzed to determine rubber content and to identify low-molecular-weight extractables. The extraction procedure was patterned after one described by Buchanan *et al.* (*12*) (see Fig. 2). Among the nearly 200 species analyzed, only *E. lathyris* appears to have a hydrocarbon content and biomass appropriate for further development.

Seeds of *E. lathyris* have been collected from around the world and are being propagated to select the most productive strains. Experiments have been initiated to determine nutritional requirements and optimal growing conditions for *E. lathyris* and to identify those factors responsible for hydrocarbon production in the plant. Various agronomic aspects are being evaluated in multihectare field plots.

Early growth data developed through field plot studies remain inconclusive with respect to potential oil production. Nonetheless, we estimate that under proper cultivating conditions including irrigation, existing strains of *E. lathyris* will produce annually more than 20 tons of dry matter per hectare. Even with an extraction rate of only 15 percent, crude oil production would thus exceed 22 barrels per hectare annually. In one California test plot we estimate a yield of about 40 tons of dry *E. lathyris* per hectare. Yields in Arizona irrigated and nonirrigated plots will be determined by mid-1980.

Alternative extraction processes and by-product evaluation studies are also under way, and by the end of this 5-year research program we hope to have determined the best plants for hydrocarbon production, and increased plant yields.

We also expect to have established a processing plant for obtaining crude oil from the dry matter, refined the crude into fuel or chemical intermediates, or both, identified valuable by-products, and brought new lands into production.

Parthenium argentatum

Guayule is a rubber-producing shrub native to the Chihuahuan Desert in southwestern Texas and northern Mexico. Tests indicate that guayule rubber has chemical and physical properties essentially identical to that produced by the rubber tree *Hevea brasiliensis*. The principal barriers to commercial development are the difficulties of establishing the plant, which is usually propagated by nursery-grown seedlings, and processing costs. Harvesting and cultivating procedures are fairly well established and are based on currently available farming equipment.

Guayule was a commercial source of rubber in the early 1900's. During World War II, personnel of the Emergency Rubber Project (ERP) planted 12,500 hectares with guayule. Of the 13 million hectares surveyed by the ERP, 1.5 million hectares in California, Texas, New Mexico, and Arizona were declared suitable for guayule cultivation. Congress planned to plant a total of 202,000 hectares, but the conclusion of World War II and the development of synthetic rubber resulted in project termination.

In the early 1970's several circumstances rekindled interest in the production of natural rubber from guayule. Increased petroleum prices resulted in an increase in the price of synthetic rubber; and natural rubber prices rose to keep pace with synthetic rubber prices. The continued availability of natural rubber supplies from foreign sources is uncertain and is a national concern. Since new extraction processes developed in Mexico have brought the quality of guayule rubber to a level equal to that of *Hevea* rubber, interest in the product continues to increase (*13*).

In 1973 the Comisión Nacional de las Zonas Áridas (CONAZA) began a guayule research and development project and established a rubber research production program in 1976. An extraction plant in Saltillo, Coahuila, Mexico, has begun small-scale processing of material harvested from wild guayule, and CONAZA estimates that a full-scale extraction plant can produce 30,000 tons of rubber annually from wild guayule plants growing in the Mexican desert regions (*14*). Experimental radial tires containing 30 to 40 percent of the guayule rubber produced in Saltillo passed all U.S. Department of Transportation high-speed and endurance tests.

The Native Latex Commercialization Act, enacted by the U.S. Congress in 1978, authorized a $30 million program of research, development, and demonstration of guayule rubber production and manufacture. A Department of Defense project is in progress to evaluate guayule rubber as a substitute for *Hevea* rubber, and additional U.S. research and

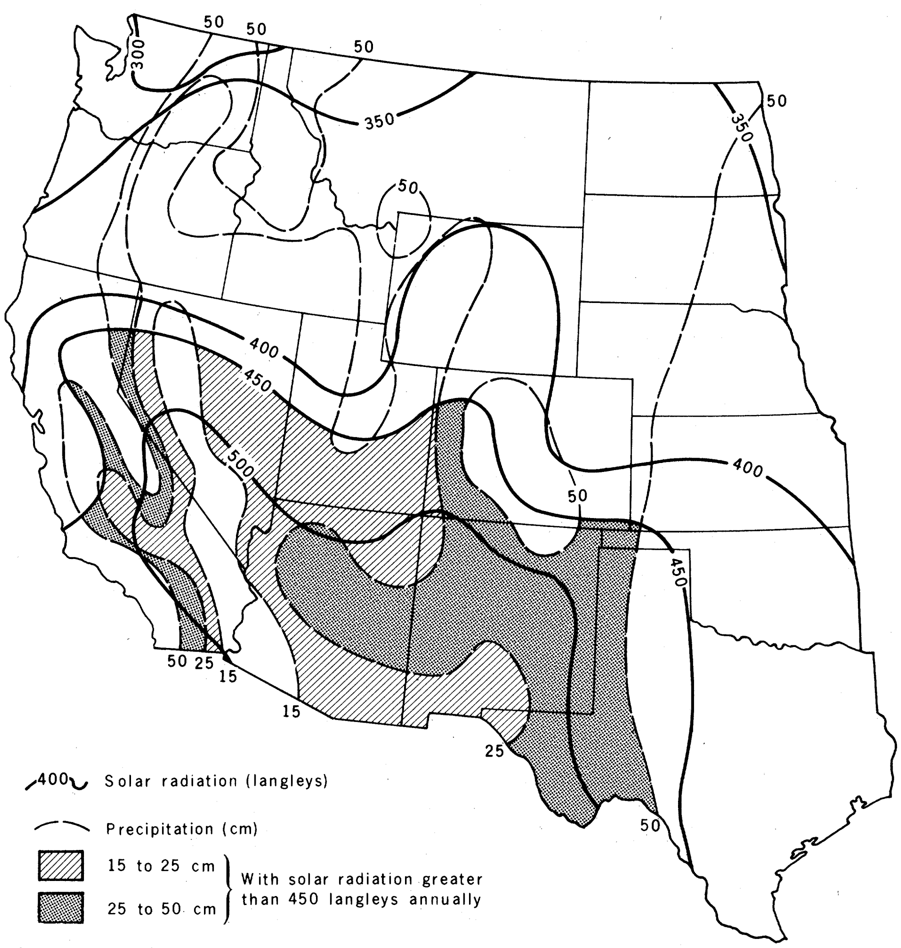

Fig. 1. Composite map of the western United States showing areas (shaded and cross-hatched) suitable for growing *E. lathyris*.

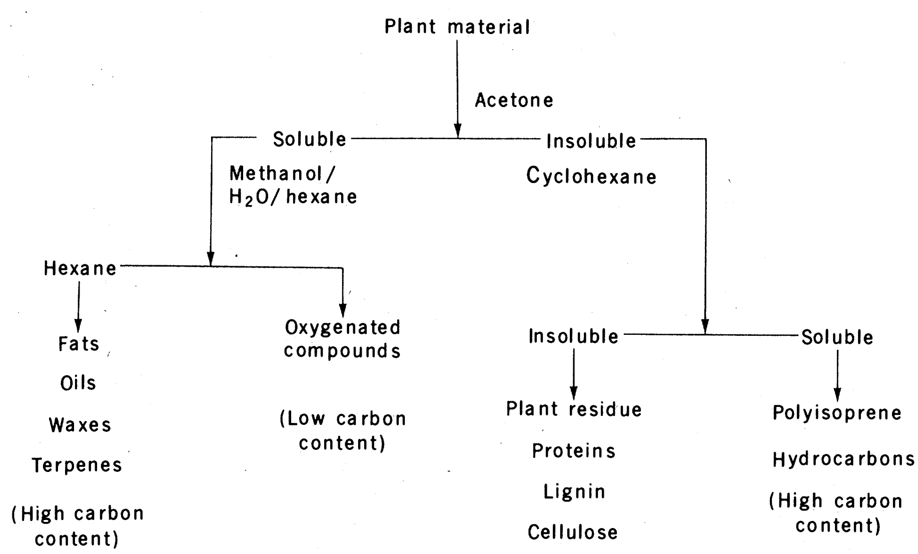

Fig. 2. Primary procedure for extraction of crude oils from *E. lathyris*.

development programs are under way through sponsorship of the U.S. Department of Agriculture, National Science Foundation, Southwest Border Regional Commission, Four-Corners Regional Commission, and the state of California.

Germ plasm collections have been made from wild guayule plants in Mexico and Texas. Plantings have been established to test yields, to increase seed supplies, and to conduct plant breeding work. Test plots have been established to determine desirable planting and cultivating practices. Research is being conducted on the possibility of increasing rubber yield by treating guayule plants with plant growth regulators.

The recent development of a seed coating process to promote germination, and the development of selective herbicides, will make direct seeding in field plantations a possibility. Eliminating nursery or greenhouse propagation could produce considerable savings in production costs.

The only guayule yield figures now available are estimates developed during the ERP. During the life of the ERP the 1800 hectares that were planted yielded, per hectare, approximately 480 kg of guayule rubber per year. Kelly (*15*) obtained yields of approximately 860 kg per hectare per year from one test plot in California. Foster *et al.* (*16*) have outlined the state of the art of guayule technology and described present and projected world rubber market conditions and areas of the United States where conditions favor guayule cultivation.

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Indoor Air Pollution, Tobacco Smoke, and Public Health

James L. Repace and Alfred H. Lowrey

Serious health effects from air pollution have led to federal standards for the regulation of outdoor exposure levels. However, Americans spend about 90 percent of their time indoors (*1*). Thus the levels of indoor air pollution are important in determining total exposure to air pollutants (*2–6*). Indeed, in a recent review article (*4*) it was concluded that indoor air pollution in public office buildings is of greater potential harm than the outdoor variety, and that these exposures may constitute a real threat to the health of many urban people. The U.S. Surgeon General asserted in his report on *Smoking and Health* that tobacco smoke can be a significant source of atmospheric pollution in enclosed areas (*7*). Some 53 million U.S. smokers consumed 615 billion cigarettes in 1978 (*8*). Thus it is apparent that indoor air pollution from tobacco smoke is pandemic.

In the presence of cigarette smoke, many normal nonsmokers experience eye and throat irritation, headache, rhinitis, and coughing; allergic persons report wheezing, sneezing, and nausea as well. Particularly acute symptoms may be found in infants, children, persons with cardiovascular or respiratory disease, and wearers of contact lenses (*7*, *9*). Determining the extent of the exposure of nonsmokers to cigarette smoke is important because smoking is a cause of chronic obstructive pulmonary disease, cardiovascular disease, and lung cancer, and is associated with cancers in other parts of the body (*7*); because these diseases also occur in nonsmokers; and because the products of tobacco combustion have been detected in nonsmokers (*10*).

Although measurements of indoor carbon monoxide pollution from smoking are abundant (*7*), published reports of the exposure of the population to the particulate phase of ambient tobacco smoke are rare (*7*, *11–13*). Furthermore, a comprehensive theory of the generation and removal mechanisms for tobacco particulates in naturally or mechanically ventilated habitable spaces has not been presented.

We therefore undertook a systematic study of the levels of respirable suspended particulates (RSP) in several common indoor environments in an attempt (i) to determine the relation of these levels to the aerosol from tobacco smoking, (ii) to understand the effect of ventilation on tobacco smoke concentra-

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