HYDROCARBON- AND RUBBER-PRODUCING CROPS

Evaluation of U.S. Plant Species

R. A. BUCHANAN,[1] I. M. CULL, F. H. OTEY, AND C. R. RUSSELL

Green plants use solar energy to produce a wide variety of products that are competitive with synthetical petrochemicals. These products include tall oil and its derivatives (fatty acids, rosin acids), naval stores (solvents, terpene resins, rosin), vegetable oils, waxes, tannins (phenolic compounds), and natural rubber (NR). Except for vegetable oils, we refer to these types of products collectively as hydrocarbons. Increasing prices and decreasing availability of petroleum may force the United States to rely more heavily on plants as a source for oils and hydrocarbons. Palm oil, for example, currently costs less to produce ($0.11 to $0.18/kg, spring 1976) than major petrochemical intermediates, and NR has always been competitive with its synthetic analogs.

Professor Melvin Calvin suggests that hydrocarbon-producing plants be studied and developed as future oil and chemical resources (1). There is increasing interest in growing green plants for direct use as fuels (2). Even more serious consideration is being given to green plants as sources of biomass for conversion to synthetic fuels and chemical feedstocks (3, 4). Such energy farming concepts may soon become practical; however, there will always be an economic advantage to direct production of materials like waxes and NR rather than (or, in addition to) fuels and basic feedstocks. NR is of particular interest because of its high value and because the present major producing area may not be able to supply the long-term demand (5).

The above considerations and our national goal of future self-sufficiency in energy and basic raw materials require that new U.S. crop sources of hydrocarbons be developed. If the whole plant is harvested and utilized (a practical requirement for Guayule and other rubber-bearing species), agricultural hydrocarbon production can be compatible with increased food and fiber production. Crops can be developed that will not only provide hydrocarbons but also fiber, protein, and carbohydrate. Furthermore, plant species are available which produce hydrocarbons on land unsuited for conventional crops. An extensive research and development program is needed to select preferred plant species, to improve them genetically, to develop their agronomy, and to provide for their practical utilization. The goal is development of practical U.S. crops as productive of oil and hydrocarbon as the *Hevea* tree, which currently can produce 2.24 t/ha/yr of NR in Southeast Asia. Yields and economic returns from such a crop are compared with those from three major U.S. crops and two species of domestic wild rubber-bearing plants in Table I. These data are based on the

---

[1] Northern Regional Research Center, Federal Research, Science and Education Administration, United States Department of Agriculture, Peoria, Illinois 61604.

Presented at the 110th meeting of the Rubber Division, American Chemical Society, San Francisco, California, October 5-8, 1976.

Received for publication February 17, 1977; accepted July 25, 1977.

Economic Botany 32: 131-145. April-June, 1978

Published for the Society for Economic Botany

TABLE I

Comparison of a Hypothetical Hydrocarbon-Producing Crop with Major U.S. Crops and Wild Rubber-Bearing Plants

Products and yields	Corn grain	Soybean	Alfalfa hay	*Apocynum cannabinum*	*Asclepias syriaca*	New crops[a]
Yield basis, per year	98 bu/acre	27 bu/acre	3 T/acre	5.5 T/acre	5.5 T/acre	10 T/acre
Yield, kg/ha/yr	6151	1816	6725	12329	12329	22416
Crude fat, kg/ha/yr	246	347	148	555	530	1345
Crude protein, kg/ha/yr	621	743	1096	1060	1369	2242
Crude carbohydrate, kg/ha/yr	4982	528	2703	---	---	---
Rubber, kg/ha/yr	---	---	---	123	173	897
Bast fiber, kg/ha/yr	---	---	---	621	621	1345
Farm value[b], $/ha/yr	656	320	408	---	---	>1000
Monetary return to primary refiner in $/ha/yr:						
Crude soybean oil[b]		134				---
Soyabean oilseed meal[b]		219				---
Whole plant oil[c]		---				178
Rubber[c]		---				609
Bast fiber[c]		---				563
Residue feed, 11% protein[c]		---				622
Total		353				1972

[a] Data in this column are not meant to serve as the specification for a new crop, but is given to provide a basis for comparison only. The assumed composition is 6% oil, 4% NR, 10% protein, and 6% bast fiber taken as reasonable values for an improved *Apocynum* or *Asclepias* variety.

[b] Based on December 1975 prices; corn $2.71/bu, soybean $4.80/bu, alfalfa $55/t, crude soybean oil $0.175/lb, and the oilseed meal $135/t.

[c] The whole plant oil valued as crude tall oil at $0.06/lb, NR at $0.308/lb, bast fiber as raw jute at $0.19/lb and the 11% protein residue at $30/t.

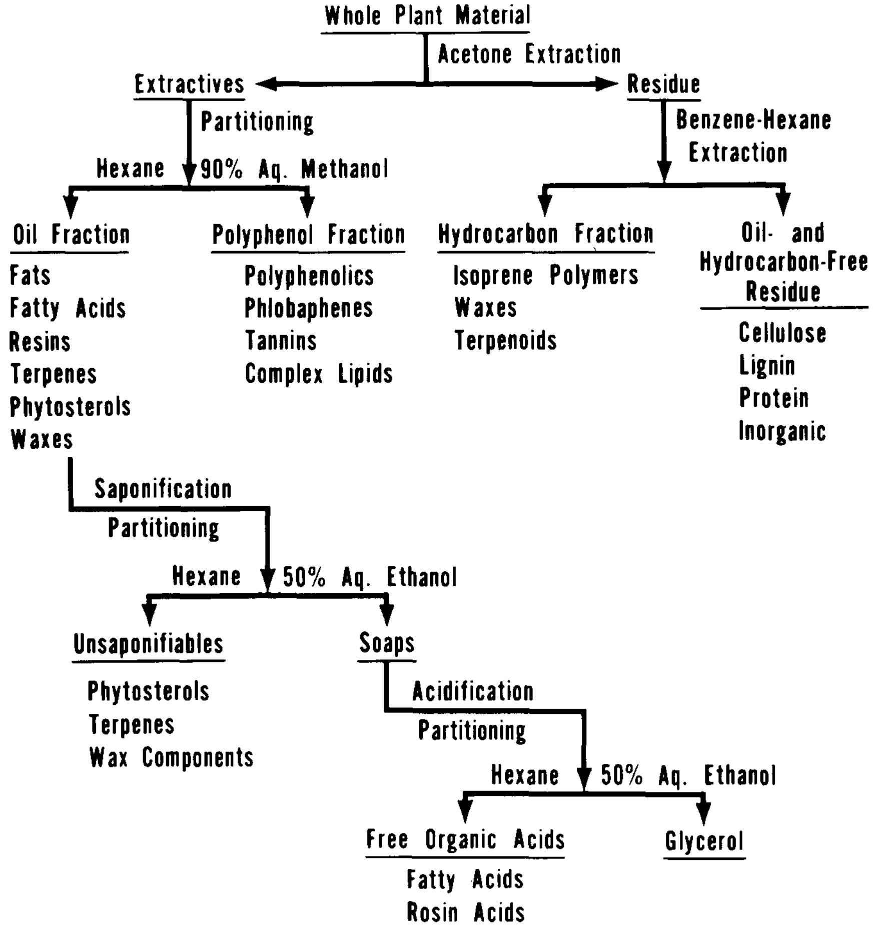

Fig. 1. Scheme for partitioning whole-plant samples.

assumption that the entire hydrocarbon-producing plant would be harvested and utilized. The comparison shows that only a three- to fivefold total genetic and agronomic improvement, i.e., about a twofold increase in biomass and about a twofold increase in total oil and hydrocarbon content, is needed to make common wild species as productive as the *Hevea* tree. The economics of such a crop appear very favorable.

Multiple-use crops go very much against recent agricultural and industrial practice in the United States. Also, sustained perennial harvesting of an entire crop plant might cause an objectionable decrease in the organic content of some soils. However, whole-plant utilization offers greatly improved productivity as seen by comparing oil and protein yields of whole plants and soybean (our major oilseed, protein crop); see Table I. Thus, research to overcome these objections is justified.

The first phase of research requires a careful selection of a limited number of plant species for detailed study. This primary selection is difficult because such a large number of species must be considered and only limited analytical

TABLE II

Rating of Plant Species According to Their Botanical Characteristics

	Rating						
	1	2		3[a]		4	5[b]
Characteristic	Perennial only	Annual	Perennial	Annual	Perennial	Annual and perennial	Annual and perennial
Growth environment:							
Aquatic							X
Terrestrial	X	X	X	X	X	X	
Mesic to subxeric	X	X	X	X	X	X	
Xeric							X
Temperate or subtropical	X	X	X	X	X	X	
Tropical							X
Growth habit:							
Adaptable to annual pollarding	Yes	--	Yes	--	No	--	--
Growth rate per year, plant height,[c] m	>1.5	>1.5	0.5-1.5	0.5-1.5	>0.5	<0.5	--
Upright	X	X	X	X	X		
Marsh plants, vines, etc.[d]						X	
Epiphytes and parasites							X

[a] Rating 3 also includes species otherwise rated 4 but which produce hydrocarbon-rich fruits, roots, rhizomes, bulbs, etc. or which are lactiferous and could produce hydrocarbons by tapping.

[b] Rating 5 applied to species having any one or more of the undesirable characteristics listed in this column.

[c] For perennial species, this is the height attained in a single growing season following clipping at near the ground level (pollarding).

[d] Rating 4 applies to all species of marsh plants, vines, rosette plants, low-growing succulents, and sod-forming grasses including those with high rates of growth.

data are available for most species. We have established a preliminary evaluation procedure for plant species based on their botanical characteristics, chemical composition, and fiber structure. Each plant species was assigned numerical ratings which can be added to give a value indicative of their potential as a hydrocarbon crop. Our evaluation procedure has been demonstrated by its application in appraisal of 106 plant species. Six of these species were rated from published data and the remaining 100 were analyzed in our laboratory.

TABLE III

Rating of Plant Species According to Their Composition

Component[a]	1	2	3	4
Fiber[b]	Fibrous	Non-fibrous	---	---
Crude protein,[c] %	>14	<14	---	---
Oil fraction, %	>8	5-8	2-5	<2
Hydrocarbon fraction, %	>2	1.2-2.0	0.4-1.2	<0.4

[a] Each species was rated independently in each of the four categories, i.e., fiber utility, protein production, oil production, and hydrocarbon production. Compare with Tables VI and VIII.

[b] Rating 1 is applied to fibrous or woody species potentially useful for fiber, papermaking, or making board products. Succulent, pulpy, nonfibrous, or nonwoody species are assigned rating 2 as are species where hydrocarbon production would involve harvesting of a produce or only tapping of a lactiferous species.

[c] Crude protein is taken as Kjeldahl N X 6.25.

EXPERIMENTAL

Plant Materials

All the initial 100 plant samples were collected from the wild near Peoria, Illinois, in September and October 1975. (*Asclepias syriaca* reaches maximum rubber content at maturity in September in Illinois, but the optimum harvest time for most other species is unknown.) Species known to be capable of producing NR were collected preferentially, but other species were included to obtain a wider representation of botanical families. Several species were thus included whose hydrocarbon content had not previously been reported. Herbaceous and small woody plants were clipped at the soil line. Only new growth of the current season was clipped for evaluation from large perennial woody plants. Leaves, fruits, and seeds were retained to give samples representative of the entire plant. Most samples included several individual plants from a single location and were larger than 500 g dry weight. Exceptions occurred for large plants where samples often represented only one plant and for small plants where insufficient material occurred at a single location. All samples were air-dried indoors then ground coarsely with a Wiley mill having a screen with 6.4-mm diameter round holes. Shortly before analysis, samples were reground using a screen with about 0.6 mm openings. Most samples contained 6% to 10% moisture, but all analytical values are reported on a dry basis.

TABLE IV
Fractionation of Plant Materials, Quality of Separation[a]

Plant fraction	Carbon values range, %	Hydrogen values range, %
Whole plant		
Analytical values, 2 samples	43.6-48.5	6.2-6.6
Polyphenol fraction		
Analytical values, 3 samples	52.1-57.0	6.7-7.7
Standard, Quercetin, $(C_{15}H_{10}O_7)$	59.60	3.38
Oil fraction		
Analytical values, 7 samples	75.6-79.7	10.8-11.4
Standard, Triolein, $(C_{57}H_{104}O_6)$	77.30	11.85
Hydrocarbon fraction		
Analytical values, 4 samples	79.9-88.1	11.0-12.6
Standard, Cetyl stearate, $(C_{34}H_{68}O_2)$	80.24	13.47
Standard, Isoprenoids $[(C_5H_8)_x]$	88.16	11.84

[a] Samples from several different plant species were analyzed and the range of values is given in comparison with calculated values for standard materials.

Analysis and Fractionation

A classic scheme was employed for partitioning whole plant samples into major fractions by solvent extraction (Fig. 1). The acetone and subsequent benzene-hexane extractions were exhaustive, requiring 24 hr or longer using Soxhlet apparatus. The solvent for extraction of hydrocarbon fraction was a 2:3 volume ratio mixture of benzene: hexane to match NR in solubility parameter. Acetone extractives were freed from solvent then partitioned between hexane and 9:1 methanol: water in separatory funnels to give oil fraction and polyphenol fraction, respectively. This fractionation procedure had the advantage over more refined analytical methods, such as gas-liquid chromatography, of giving only a definite number of fractions so that it was easy to directly compare species which might vary in detailed composition. Also, the crudely frac-

TABLE V
Precision of Plant Fractionations Calculated from Duplicates

Plant fractions, analysis	Number of pairs	Standard deviation
Polyphenol	51	1.2%
Oil	53	0.29%
Hydrocarbon	52	0.06%
Unsaponifiables, oil fraction	7	1.6%
Free acids, oil fraction	7	1.1 g/100 g
Neutral equivalent of free acids	7	4.7

tionated products are more representative of potential commercial products than pure materials would be.

The oil fraction of plants rich in hydrocarbon was saponified and separated into unsaponifiable matter and free acids by usual procedures (6). Free acids were titrated with standard sodium hydroxide to obtain neutral equivalents (6). A few oil fractions were examined by thin-layer chromatography (TLC).

Hydrocarbon fractions of plants rich in this product were examined by infrared (IR) spectroscopy to determine whether they were predominantly NR, waxes, or mixtures. A few NR samples were purified and examined by proton nuclear magnetic resonance (PMR) and gel-permeation chromatography (GPC).

Rating of Plant Species

Botanical Characteristics. Plant species were classified into five groups according to their probable adaptability as crops for the United States and their probable yield of biomass, see Table II. For a practical crop in the United States, a species must be adaptable to mechanical planting, cultivation, and harvesting with low labor costs.

Composition. Plant species were rated according to their probable utility as sources of fiber and protein and according to their oil fraction and hydrocarbon fraction as shown in Table III.

Each species was rated independently in each of the four categories, i.e., in two classifications for fiber utility, two classifications for protein production, and four classifications each for oil and hydrocarbon production respectively (compare Table III with Tables VI and VIII).

Total Point Value. By adding the ratings in each category (see Tables II and III), a cumulative score was assigned to each plant species. An ideal candidate for development into a hydrocarbon crop would have a score of 5, whereas

TABLE VI

Evaluation of Species Previously Considered for U.S. Production of Rubber[a]

Species	Common name	Botanical evaluation	Fiber utility	Protein production	Oil production	Hydrocarbon production	Total score
Asclepias subulata Decne	Desert Milkweed	1	1	2	3	1	8
Chrysothamnus nauseosus (Pall) Britton	Rabbitbrush	1	1	2	3	1	8
Cryptostegia grandiflora R. Br.	Madagascar Rubber Vine	3	1	2	3	1	10
Parthenium argentatum Gray	Guayule	2	1	2	2	1	8
Solidago edisoniensis	Edison's Goldenrod	1	1	2	3	1	8
Taraxacum Kok-saghyz Rodin	Russian Dandelion	3	2	2	4	1	12

[a] These species were rated from data in literature sources cited in the text.

TABLE VII

Data from Examination of Wild Plants[a]

Genus - species	Common name	Ash,[b] %	Crude protein,[b] %	Acetone extractives[b]		Characterization of oil fraction[c]			Hydro-carbon fraction[b] %	Characterization of hydrocarbon fraction[d], %	Literature values[e], crude rubber, %	
				Polyphenol fraction, %	Oil fraction, %	Unsaponifiable matter, %	Free acid, yield, g/100 g	Free acid, neutral equivalent			Low	High
Anacardiaceae												
Rhus glabra L.	Smooth Sumac	6.88	6.56	18.8	5.51	55.4	38.3	336	0.20		0.08	0.26
Apocynaceae												
Apocynum cannabinum	Indian Hemp	7.38	8.63	7.7	4.48	43.7	48.5	320	1.01	NR and wax	0.35	1.3
Asclepiadaceae												
Asclepias incarnata L.	Swamp Milkweed	9.80	6.50	6.5	4.71	25.2	66.1	310	0.67	NR	0.33	2.6
Asclepias syriaca L.	Common Milkweed	9.86	11.06	7.2	4.28	39.4	54.0	293	1.39	NR	0.52	2.3
Asclepias verticillata L.	Whorled Milkweed	7.89	10.25	9.0	4.51	32.4	60.0	305	0.97	NR	1.2	2.4
Caprifoliaceae												
Sambucus canadensis L.	Common Elder	4.47	6.19	6.3	2.13	49.2	38.7	337	0.50	NR	0.07	1.3
Compositae												
Ambrosia trifida L.	Giant Ragweed	7.97	10.50	4.1	7.60	8.9	84.0	297	0.55	NR		0.27
Aster novae-angliae L.	New England Aster	7.39	7.44	5.5	1.50	43.2	46.7	345	0.50	NR	0.11	0.20
Eupatorium altissimum L.	Tall Boneset	6.51	8.00	7.9	5.21	42.6	49.9	301	0.35	NR and wax		0.26
Silphium laciniatum L.	Compass Plant	9.01	8.94	7.4	3.00				0.68	NR	0.28	0.90
Solidago altissima L.	Tall Goldenrod	9.46	6.38	5.2	2.53	39.8	49.6	318	0.83	NR and wax	0.42	1.4
Sonchus arvensis L.	Sow Thistle		9.25	11.0	5.32	59.6	32.0	319	0.72	NR and wax	0.38	1.2
Euphorbiaceae												
Euphorbia cyparissias L.	Cypress Spurge	8.70	9.69	6.0	6.32	59.1	30.7	463	0.30	Wax	0.14	0.72
Euphorbia supina Raf.	Prostrate Spurge	11.21	9.69	12.9	4.72	63.4	26.3	307	0.55	NR and wax		
Labiatae												
Monarda fistulosa L.	Wild Bergamot	7.15	7.75	6.4	2.17				1.15	NR	1.5	2.5
Phytolaccaceae												
Phytolacca americana L.	Pokeweed		15.50	5.9	3.41				0.17		0.0	0.28

[a] Data from examination of 100 plant species is available from the senior author.

[b] Expressed as percentage of the whole dry plant.

[c] Calculated on the basis of oil fraction only.

[d] Characterized by infrared spectoscopy, see Figure 2. *NR indicates that the hydrocarbon was predominately NR, wax indicates that there was little NR.*

[e] Data scattered in the open literature on analysis of U.S. plant species for rubber content, reference 12 is the largest source.

TABLE VIII

Evaluation of Plant Species for Potential as Hydrocarbon-Producing Crops[a]

Genus - species	Common name	Botanical evaluation	Fiber utility	Protein production	Oil production	Hydrocarbon production	Total
Anacardiaceae							
Rhus glabra L.	Smooth Sumac	1	1	2	2	4	10
Apocynaceae							
Apocynum cannabinum L.	Indian Hemp	2	1	2	3	3	11
Asclepiadaceae							
Asclepias incarnata L.	Swamp Milkweed	1	1	2	3	3	10
Asclepias syriaca L.	Common Milkweed	1	1	2	3	2	9
Asclepias verticillata L.	Whorled Milkweed	2	1	2	3	3	11
Caprifoliaceae							
Sambucus canadensis L.	Common Elder	1	1	2	3	3	10
Compositae							
Ambrosia trifida L.	Giant Ragweed	2	1	2	2	3	10
Aster novae-angliae L.	New England Aster	2	1	2	4	3	12
Eupatorium altissimum L.	Tall Boneset	1	1	2	2	4	10
Silphium laciniatum L.	Compass Plant	1	1	2	3	3	10
Solidago altissima L.	Tall Goldenrod	2	1	2	3	3	11
Sonchus arvensis L.	Sow Thistle	2	1	2	2	3	10
Euphorbiaceae							
Euphorbia cyparissias L.	Cypress Spurge	3	1	2	2	4	12
Euphorbia supina Raf.	Prostrate Spurge	4	1	2	3	3	13
Labiatae							
Monarda fistulosa L.	Wild Bergamot	2	1	2	3	3	11
Phytolaccaceae							
Phytolacca americana L.	Pokeweed	1	1	1	3	4	10

[a] The evaluation of 100 plant species is available from the senior author.

a species useless for both hydrocarbon and oil production would score 17. A species ideally suited for either hydrocarbon or oil production, but not both, would score 8. Thus, species scoring 11 or less are considered possibilities and those scoring 8 or less are of definite interest.

RESULTS AND DISCUSSION

Partitioning Procedures

The quality of separation achieved in partitioning the plant materials was estimated by carbon-hydrogen analysis of representative fractions (Table IV). Wide differences in solubility parameters of the partitioning solvents resulted in good separation into distinct fractions.

The precision of the fractionations is shown in Table V. In replicate analysis of a given sample, the values for hydrocarbon fraction and oil fraction are much more precise than the values for polyphenol fraction. The more polar portion of the polyphenol fraction is sparingly soluble in acetone and tends to be incompletely extracted.

Evaluation of Previously Considered Species

During World War II, the U.S. Department of Agriculture gave serious attention to Guayule, Russian Dandelion, Madagascar Rubber Vine, Rabbitbrush, and Edison's selected Goldenrod species as sources of NR (7). Certain desert milkweeds have also been suggested (8). Thus, there is ample data in the literature for application of our rating system to these species (Table VI).

Guayule, which is scored at 8 in our evaluation scheme, is currently being investigated as a crop for Israel, Mexico, and the United States (9). It chiefly needs improvement in yield and adaptation to a more northern climate to become a very useful U.S. crop. High resin production of Guayule was considered a liability in the past but now must be considered an asset because waxes and terpene hydrocarbons have increased in value relative to rubber and are in short supply.

Russian Dandelion is rated lower than the other species in Table VI because of its poorer botanical characteristics. In the 1941–1946 study, this species was found difficult and expensive to grow and harvest in the United States. It is a rosette plant with the root as harvestable produce and would require considerable improvement in vigor, size, and rubber content. However, such improvement has been judged feasible with relatively little difficulty and at reasonable expense (10).

The Madagascar Rubber Vine (*Cryptostegia*) also has poor botanical characteristics for a U.S. crop plant. (It was rated 3 rather than 4 in botanical characteristics because it is lactiferous and has been tapped by clipping tips of the vine. Also, it may be kept pruned to a shrub-like habit.) A sufficient genetic and agronomic effort with this species might also result in a practical U.S. crop (11).

Thus, all the plant species in Table VI are potential U.S. crops and deserve new research emphasis.

Examination of One Hundred Species of Wild Plants

Nearly 300 species of rubber-bearing plants (containing more than about 0.5% NR) that grow in the United States can be identified in the literature. However, more information on the composition of many of these species is needed to properly evaluate them.

Data from examination of 100 Illinois plant species in 77 genera and 45 families are available from the senior author. Here, representative data are presented for only 16 of the more interesting plants (Table VII). Eighteen rubber-bearing species were included in our sample of 100, four of which had not been identified in the literature, although related species were. *Monarda fistulosa* is an outstanding rubber-bearing species both for the amount and the quality of its NR. Among those who previously analyzed plants for NR, only Edison appears to have recognized that the Labiatae merit special consideration (12).

The polyphenol fraction is reactive and potentially valuable for making adhesives, phenolic resins, antioxidants, and other products. The species highest in this was *Rhus glabra*, which has been a source of commercial tannin.

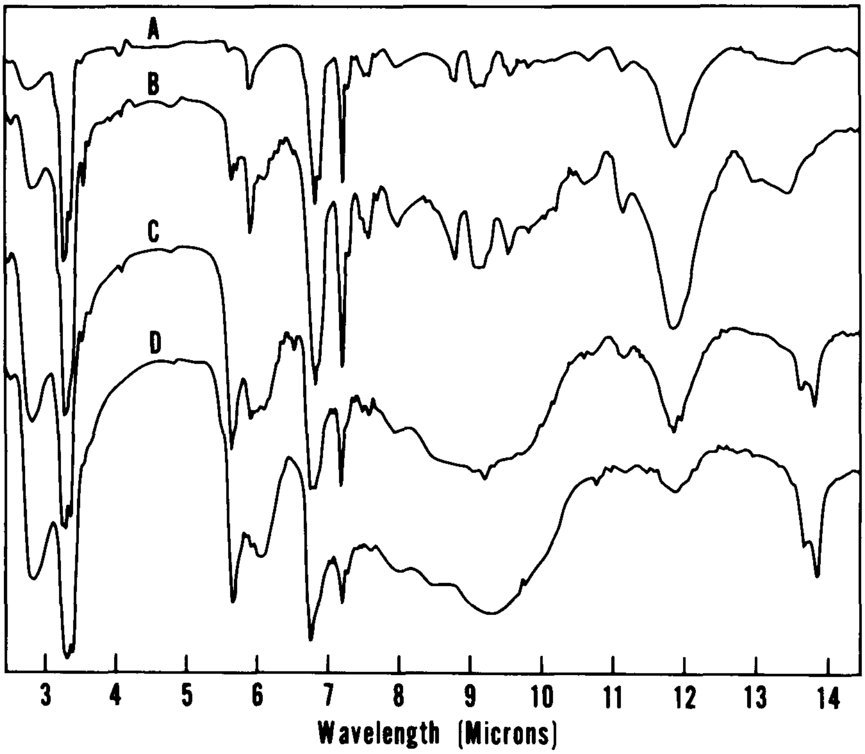

Fig. 2. Infrared spectra of typical plant hydrocarbon fractions. A, acetone extracted SMR 5L natural rubber from *Hevea brasiliensis*; B, hydrocarbon fraction from *Monarda fistulosa*; C, hydrocarbon fraction from *Eupatorium altissimum*; D, hydrocarbon fraction from *Euphorbia cyparissias*.

The oil fractions are much different from usual vegetable oils, obtained from fruits or seeds, as shown by their high content of unsaponifiable matter (Table VII) and confirmed by TLC of a few preparations. Whole-plant oil fractions are like the crude fat content of forages and may also be considered as unsaponified tall oils. Generally, the crude products are dark and melt slightly above room temperature into low viscosity fluids. They are potentially useful as substitutes for petrochemicals at prices below the cost of usual vegetable oils. Of course, edible products could be prepared from them. Six species analyzed more than 6% oil fraction and their potential appears greater than that of usual oilseed crops (compare Table I).

Initial characterization of hydrocarbon fractions was by IR spectroscopy as illustrated in Figure 2. A few species gave a spectrum identical with *Hevea* NR, but most gave a spectrum indicating some wax contamination. The presence of wax-esters in hydrocarbon fractions from many plants was indicated by carbonyl absorption at about 5.7 μm and hydrocarbon crystallinity absorption, split peaks, at about 13.7 μm. The relative amounts of wax and NR was estimated roughly by comparing these peak heights with the *cis*-CH_3 absorption peak at about 11.95 μm for natural rubber. Some of the wax-NR mixtures were difficult to separate and this may partially account for previous reports that Goldenrod and

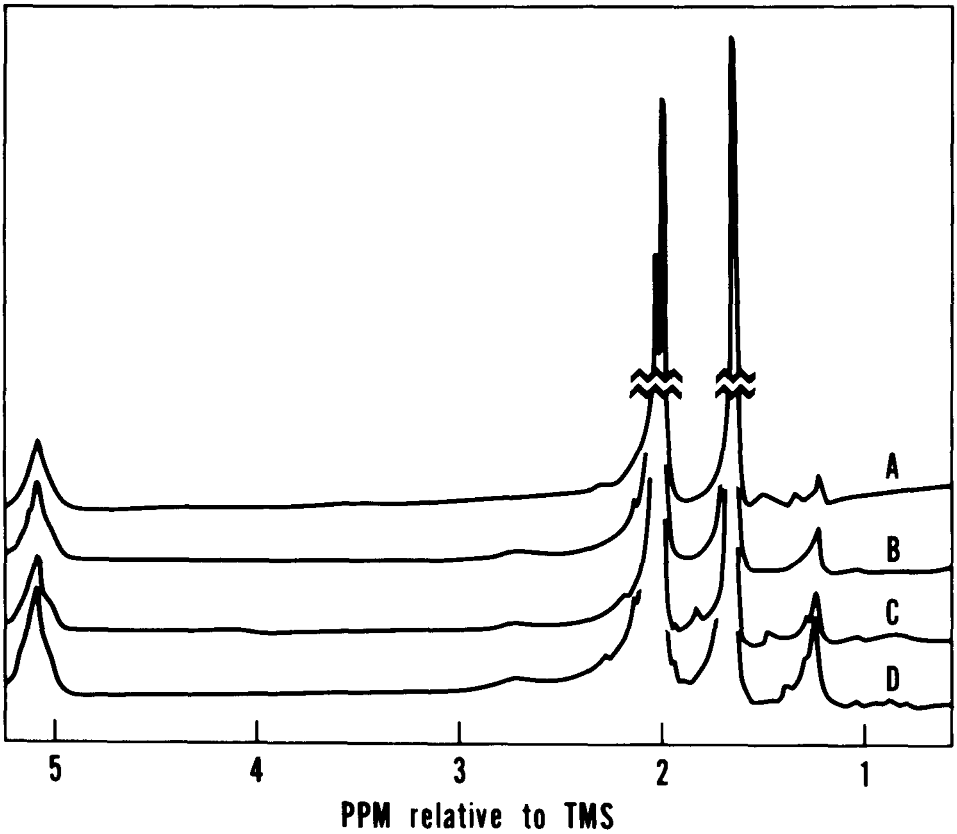

Fig. 3. PMR spectra of purified samples of typical plant hydrocarbon fractions. **A**, acetone extracted SMR 5L natural rubber from *Hevea brasiliensis*; **B**, hydrocarbon fraction from *Monarda fistulosa*; **C**, hydrocarbon fraction from *Aster nova-angliae*; **D**, hydrocarbon fraction from *Asclepias syriaca*.

Milkweed rubbers had low molecular weights. Also, many of the older literature values for crude rubber content describe very impure hydrocarbon fractions.

PMR spectra were obtained for purified samples of hydrocarbon fraction from eight species (*Apocynum cannabinum, Asclepias syriaca, Asclepias verticillata, Aster nova-angliae, Euphorbia supina, Monarda fistulosa, Solidago altissima*, and *Sonchus arvensis*) and found to be identical with the spectrum for *Hevea* NR except that slight oxidation had occurred during some of the sample preparations (Fig. 3). The *cis*-configuration was shown by resonance at 1.69 ppm and the absence of *trans* by complete absence of resonance at 1.62 ppm. Oxidation was indicated by resonances at 1.30 ppm and 2.68 ppm (13). There is no evidence for either 1,2- or 1,4-addition polymer in any of the IR or PMR spectra.

Gel permeation chromatography of the same eight samples indicated that their average molecular weights may be substantially lower than that of *Hevea* NR as previously reported for leaf rubbers (7, 11). However, this may have been entirely or partially an artifact arising from our method of gel removal. Both polyisoprene microstructure and molecular weight are genetically controlled and, therefore, subject to manipulation while improving a crop plant (9).

TABLE IX

Species with Good Potential for Both Papermaking[a] and Hydrocarbon Production

Genus--species	Hydrocarbon crop rating	Fiber crop rating[b]	Alpha cellulose, %	Maceration yield, %			Average fiber length,[c] MM
				Bast fiber	Woody fiber	Total	
Ambrosia trifida L.	10	9	30.3	2.8	47.6	50.4	0.50
Asclepias incarnata L.	10	8	29.9	10.7	47.1	57.8	0.81
Asclepias syriaca L.	9	8	31.2	14.2	28.9	43.1	1.31
Sambucus canadensis L.	10	9	28.3	10.1	49.3	59.4	0.57
Silphium laciniatum L.	10	9	25.1	22.6	26.8	49.4	1.12

[a] Data on papermaking properties are from reference 14.

[b] Rated on a scale where 8 indicates potential pulping materials and 10-11 indicates promise, higher scores indicate less promising species, see reference 14.

[c] Arithmetic mean of combined bast and woody fiber.

Evaluation of the One Hundred Species of Wild Plants

All species evaluated were given a numerical value according to the rating scales listed in Tables II and III and these ratings are available from the senior author. Ratings for the 16 species of Table VII are given in Table VIII. Most of the 100 plants had good botanical and fiber ratings while their protein, oil, and hydrocarbon ratings were generally poor. Of the 100 species evaluated, nine were assigned a cumulative score of 10 or less and hence deserve further evaluation and consideration as new U.S. crops. *Ambrosia trifida, Asclepias incarnata, Asclepias syriaca, Sambucus canadensis, Silphium laciniatum,* and *Sonchus arvensis* are rubber-bearing species. *Eupatorium altissimum, Phytolacca americana*, and *Rhus glabra* produce less hydrocarbon fraction but are productive in oil fraction. *Phytolacca americana* has some significance as a food plant and is rich in protein. *Rhus glabra* is of interest for its content of both oil fraction and polyphenol fraction. The highest rated species is common milkweed, *Asclepias syriaca*, which has previously been suggested as a crop plant for its rubber, fluff, bast fiber, and seed (14).

Our laboratory has previously evaluated five or the nine highest rated species as having good potential as fiber crops for papermaking (15) (Table IX). Another high-rated species, *Eupatorium altissimum*, probably also has potential as a fiber crop for papermaking but has not been evaluated. Extraction of oil and hydrocarbon is compatible with the papermaking process and such multiple-use plant species are of particular interest.

SUMMARY

Currently there is interest in various energy farming concepts to grow green plants for direct use as fuel, or as a source for biomass conversion to synthetic fuels and chemical feedstocks, or as a method of synthesizing hydrocarbons such as rubber with specific end-use applications. The latter alternative is the most practical and will increase in importance. Direct production will usually be much more economical than producing fuels or basic feedstocks, then subsequently converting them to end-products. Agricultural production of hydrocarbons need not be incompatible with food and fiber production because full utilization of the plant material would also provide fiber, carbohydrate, protein, and other products. Furthermore, some hydrocarbon-producing plants can grow on land unsuited for conventional crops. It appears technically and economically feasible to develop a U.S. crop that is as productive in hydrocarbons as the *Hevea* tree currently is in southeast Asia. For practical agricultural production of hydrocarbons in the United States, highly productive species adaptable to our situation must be selected. Preferably, the selection should be made from the viewpoint of utilizing the entire plant.

We have described an evaluation procedure for primary selection of candidate plant species for development into hydrocarbon producing crops. However, relatively few species have been evaluated to date.

At least 12 U.S. plant species appear suitable for development as crops for NR production. Three other species, which produce little or no rubber, appear to have potential for the production of a whole-plant oil. Five or six species appear especially suited for combined production of NR and paper pulp.

ACKNOWLEDGMENTS

John McBrien for extraction of plant materials, Clara E. Johnson for analysis, Larry W. Tjarks for nuclear magnetic resonance, and Charles L. Swanson for gel-permeation chromatography.

LITERATURE CITED

1. **M. Calvin.** *Science* 184(4134): 375 (1974).
2. **G. C. Szego and C. C. Kemp.** *Chem. Technol.* 275 (May 1975).
3. **A. H. Brown.** *Chem. Technol.* 434 (July 1975).
4. *Chem. Eng. News* 54(8): 24 (Feb. 23, 1976).
5. *Rubber World* 173(4): 26 (1976).
6. **L. V. Cocks and C. van Rede.** "Laboratory Handbook for Oil and Fat Analysts," Academic Press, New York and London (1966).
7. **H. L. Trumbull.** *Ind. Eng. Chem.* 34(11): 1328 (1942).
8. **H. M. Hall and F. L. Long.** "Rubber Content of North American Plants," Carnegie Institution of Washington (1921).
9. **W. G. McGinnies and E. F. Haase (eds.).** "An International Conference on the Utilization of Guayule," Proceedings of Meeting held at Tucson, Arizona, November 17–19, 1975.
10. **W. G. Whaley and J. S. Bowen.** "Russian Dandelion, An Emergency Source of Natural Rubber," USDA Miscellaneous Publication No. 618 (1947).
11. **S. R. Hoover and Co-workers.** *Ind. Eng. Chem.* 37(9): 803 (1945).
12. **L. G. Pohlhamus.** "Plants Collected and Tested by Thomas A. Edison as Possible Sources of Domestic Rubber." ARS 34-74, U.S. Department of Agriculture, July 1967.
13. **M. A. Golub, M. S. Hsu, and L. A. Wilson.** *Rubber Chem. Technol.* 48(5): 953 (1975).
14. **B. Beckman.** *Econ. Bot.* 3(3): 223 (1949).
15. **H. J. Nieschlag and Co-workers.** *Tappi* 43(3): 193 (1960); **H. J. Nieschlag and Co-workers.** *Tappi* 43(12): 993 (1960); **G. H. Nelson and Co-workers.** *Tappi* 49(1): 40 (1966).