Guayule for Rubber Production in Arizona

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COVER: Six-month old guayule transplant near Tucson, Arizona

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Foreword

This bulletin is based on information available from literature, current research and general knowledge of the authors and contributors. It is intended to serve as a guide for those interested in guayule, including growers, industry and researchers. Guayule research at The University of Arizona has been on a continuous basis since 1976. It has been funded by the Arizona Agricultural Experiment Station, Four Corners Regional Commission, the National Science Foundation, and the Joint Guayule Commission through the U. S. Department of Agriculture. Research is in progress in many areas and more information is continuously being developed.[1]

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[1] Additional research is being conducted at New Mexico State University, Texas A&M University, University of California, Los Angeles Arboretum, Goodyear Tire and Rubber Company, Firestone Tire and Rubber Company, Pennzoil, the U. S. Department of Agriculture, California Department of Food and Agriculture and others. Some of the information included in this bulletin is based on information obtained from these institutions through formal and informal exchanges.

Contents

I. Introduction

Guayule (pronounced wy-oo-lee) (Parthenium argentatum, Gray) is a rubber producing, perennial shrub native to the desert plateaus of southwest Texas and north central Mexico. It is one of 2,000 species of plants that produce rubber.

A. Importance of guayule

Guayule is important because it is the main species, which produces commercial quantities of natural rubber, that is adapted to the United States, particularly the Southwest.

1. Need for natural rubber

Natural rubber is preferred to synthetic rubber where low heat buildup, elasticity and resilience are necessary. It is required in high speed tires when severe driving conditions require these properties in the rubber. In 1979 the United States used more than 750,000 tons (680,000 metric tons) of natural rubber, all of it imported. Projections for 1990 show the amount of rubber needed will approach 1 million tons (0.9 million metric tons) per year.

2. Government interest

Congress passed the "Native Latex Commercialization Act of 1978" to promote the development of guayule because of rubber's importance to the defense, economy and well-being of the nation. As a result, the U.S. Departments of Agriculture, Commerce, Defense, and Interior and the National Science Foundation have provided financial resources for research and development directed toward a domestic supply of natural rubber.

A domestic rubber supply would meet strategic needs and would reduce the impact of disrupted import supplies. Since all natural rubber is currently imported, a domestic rubber source could affect the balance of payments. Guayule also could reduce the use of limited petroleum supplies for synthetic rubber.

3. Agricultural interest

Guayule is of interest in Arizona because it can survive on less water than crops currently grown and could replace some of these crops. Guayule also may provide an alternative crop in a crop rotation cycle for efficient utilization of land, water and equipment.

B. History

The Aztecs in north central Mexico were probably the first users of guayule rubber. The conquering Spaniards discovered Aztecs playing with bouncing rubber balls. In 1852 guayule was rediscovered by a Mexican Boundary Survey party. In the late 1800s guayule was used as a source of natural rubber, becoming a major source of rubber by the early 1900s for Mexico and the United States. However, shrub supplies from native stands in Mexico were depleted so rapidly that by 1912 several rubber mills were closed. Threatened by the Mexican Revolution, the Intercontinental Rubber Company transferred its guayule operations from Mexico first to California. Then, in 1916 to the area now known as Continental in the Santa Cruz Valley south of Tucson. The guayule grew very well, but the varieties grown were low in rubber content. After fire destroyed the company's headquarters building, the operations were moved to Salinas, California, where new selections had higher rubber contents. Between 1931 and 1941 more than 3 million pounds (1.36 million kg) of rubber were produced, primarily in the Salinas Valley.

In 1942, after rubber supplies from the Far East were cut off, the U. S. government purchased the domestic Intercontinental Rubber Company holdings and established the Emergency Rubber Project (ERP) to administer a guayule production program. In addition to the plantings in California, plots were grown in Arizona and Texas. Nearly 3 million pounds (1.36 million kg) of rubber were processed in 3 1/2 years. With the end of World War II and development of synthetic rubber, the project was terminated. Limited research continued until 1959 and included seed production, cultural practices, breeding, genetics, biochemistry, physiology, grafting, extraction and processing. Results from these plantings and studies provided the starting point for current research efforts and production information.

II. Adaptation

A. Climate

Guayule has survived in temperatures from 0°F-120°F (-18°C-49°C). Some plants may be killed by temperatures below freezing, but sudden temperature drops can be most harmful to succulent plants. Hardening the plants by limiting water increases plant survival during low temperatures.

Guayule can survive several months without rainfall. In its native habitat, 9-16 inches (230-400 mm) of rain falls annually, mostly during the warmer portions of the year.

B. Soils and terrain

In its natural habitat guayule is found on shallow, calcareous, stony soils that are well drained. It usually grows in scattered patches on sloping terrain at altitudes from 3,000-7,000 feet (900-2,100 meters). In Arizona guayule is adapted to irrigated southern and western areas below 5,000 feet (1,500 m) elevation.

III. The Guayule Plant

A. Plant description

Guayule (Parthenium argentatum, Gray) belongs to the family Compositae. It is a bushy shrub that may grow from 20-50 inches in height (0.5-1.3 meters), depending on its habitat. It has a strong tap root with deep fibrous roots, a thick crown and dense branches. The leaves are long and narrow and grow in compact clusters. The gray-green color comes from the tufts of whitish trichomes and wax on the surface of the leaves (see front cover and Fig. 1). The plant flowers profusely with each branch terminating in an

Figure 1. Sketch of a guayule branch showing characteristics of leaves, inflorescences and general appearance (Redrawn from Hammond and Polhamus, 1965).

inflorescence. The seeds are small with approximately 450,000 per pound (1,000 seeds per gram). Rubber is produced in individual cells through the plant roots, stems and branches; no rubber is produced in the leaves.

B. Growth

Guayule seeds will germinate at a minimum temperature of 50°F (10°C) however, the best germination and growth rates occur at temperatures from 70°F-90°F (20°-32°C). The dicotyledonous seedlings are very weak and grow slowly, forming about one leaf per week under ideal greenhouse conditions. However, the growth rate is much slower under field conditions. After about three months the stems begin to lignify, becoming woody during the first year of growth.

Growth rates depend mostly on moisture availability and temperature. Under cultivation, guayule responds rapidly to differences in moisture during the summer. The plant may become dormant during the winter, when near freezing temperatures occur, or during the summer when soil moisture is low. During droughts, the lower leaves shrivel and die. Depending on the degree of moisture stress, the upper leaves may curl and turn gray, but these can turn green if moisture becomes available.

C. Flowering and seed production

The main shoot and all subsequent branches terminate in an inflorescence (Fig. 1). The flowering stalk is a compound cyme with the main stem and secondary stems bearing a cluster of heads. Each head has five ray-florets (seed-producing) on the periphery and numerous disk-florets (pollen-producing) in the center.

Flowering will cease during periods of very cool temperatures and with high moisture stress. Abundant flowering occurs in the spring; additional flowering occurs in the summer and fall if moisture is adequate. The best seeds are produced in April, May, early June, October and November in Arizona. During the hot summer months seeds are poorly filled and low in quality.

D. Rubber

Rubber accumulates as a latex in individual parenchyma cells rather than in continuous vessels as in Hevea trees (the source of most natural rubber). Most of the rubber is in the bark of roots, stems and branches; however, there is also rubber in the pith. Guayule rubber is a cis-polyisoprene, a long chain polymer with a molecular weight of 1.5-2.0 million. The accumulation of rubber in the various plant parts depends on the age of the plant, light intensity, moisture availability, temperature, morphology of the plant and season of year. The actual percentage of rubber will vary from less than 1 percent in young seedlings to approximately 7 percent in 3-year-old plants. Much older plants in native stands may have 10-15 percent rubber.

E. Resin

Resin forms in canals in the stems of guayule. The resins consist of terpenes, sesquiterpenes, diterpenes and triglycerides. The gum exudate seen oozing from an injured stem is mostly a sesquiterpene, Guayulin A. One of the main triglycerides is linoleic acid. The chemical composition of part of the resin has not yet been identified. Additional research is needed to determine the economic benefits and uses of the resins.

IV. Varieties

A. Previous varietal development

The Intercontinental Rubber Company is credited with domesticating and developing the first guayule variety. The company's program involved collecting hundreds of plants from the wild in Mexico for evaluation at Valley Center, California, in 1912. The breeding and selection program was transferred to Continental, Arizona, in 1916 and to Salinas, California, in 1925. The Intercontinental Rubber Company also conducted an extensive testing program from Texas to central California. Variety 593 was a selection made at Salinas in the early 1920s and was the principal variety produced during the 1920s, 1930s and the ERP.

Important germplasm was added through breeding, genetics and collection expeditions to Mexico by ERP personnel in 1942 and 1948. After World War II, the U.S. Department of Agriculture continued guayule investigations until 1959. Seeds from the best 25 breeding lines and varieties were deposited at the National Seed Storage Laboratory at Fort Collins, Colorado.

B. Present varieties and breeding lines

In 1976, seeds of the 25 breeding lines and varieties were obtained from the National Seed Storage Laboratory and were planted at the University of Arizona's Experiment Farm at Mesa, to increase seed supplies and begin the present development program. Seeds from these plantings were used to plant other observation nurseries and to perform yield tests in Arizona, California, Nevada, New Mexico and Texas. In 1980, lines 11591, 11604, 11605, 11619, 12229, N565 and N576 were selected for increase because of favorable rubber yield, rubber percentage, frost tolerance, disease resistance, apomictic behavior, seed quality and other agronomic characteristics. In 1983 these were released as varieties. Continued testing may show which of the seven varieties perform best at different locations.

Previous data from the ERP and other experiments show yields of 200-500 pounds per acre (220-560 kg per hectare) annually on a 4- or 5-year basis with the higher yields generally occurring in California. Results for improved varieties in Table 1 show yields up to 450 pounds per acre (500 kg per hectare) annually in Arizona. In a few instances yields from very small plots have reached 600-700 pounds per acre (670-780 kg per hectare) annually. (Most yield data are projections based on whole plants dug from small plots.)

The data for Tucson and Mesa (Table 2) show no yield increase after 3 years. A possible explanation is that the plants have reached a mature size where new branches on top simply replace the rubber lost from lower, shaded branches, which frequently die. This suggests that harvesting should occur when the plants are about 3 years old. It should be noted that the average yields in Tucson are higher than those at Mesa. This could be the result of plant spacing, soils, climate, or management differences. The varieties also responded differently at the two locations.

Research is in progress to determine the optimal time for harvest in terms of season. According to Table 3 rubber percentage decreases during June and July when rapid growth occurs, which increases dry matter. During the cool months rubber content and yield increase reaching a peak about March and April.

Preliminary data indicate that it may be possible to harvest by clipping 1- or 2-year-old plants and then to produce additional harvests from the regrowth. This has the advantage of reducing establishment costs, which are a major production cost. Certain varieties undoubtedly will respond to clipping better than others.

Resin content and yield are included in Table 3. The percentage of resins tends to be lowest in October, November, December and January. Resin yield shows a large increase in June coincident with the increase in dry matter resulting from spring growth.

Table 1. Average dry weight, rubber content and rubber yield for five guayule varieties; planted[1] November 1981, Tucson, Arizona, harvested April 1984.

Variety	Dry Weight lbs/A	Rubber Percent	Rubber Yield lbs/A[2]
N565	22,530	4.73	1,065
N576	14,720	5.21	765
N396	22,960	4.95	1,135
11619	19,970	5.32	1,065
593	18,545	4.20	780

[1] Planted 1 row per bed on 27-inch (0.68 m) beds; plant spacing 14 inches (0.35 m).

Table 2. Average rubber yields and rubber percentages of twenty guayule varieties in Arizona at Tucson and Mesa experimental farms, sampled after 2, 3, and 4 years of growth.

Location	Average Rubber Percentage			Average Rubber Yield, lbs/Acre		
	2 yrs.	3 yrs.	4 yrs.	2 yrs.	3 yrs.	4 yrs.
Tucson[1]	4.6	5.6	5.1	1180	1460	1465
Mesa[2]	5.0	4.8	4.4	450	1150	1095

[1] Planted May 1978 on 27-inch (0.68 m) beds, with one row per bed; plant spacing 14 inches (0.35 m). Harvested in 1980, 1981, and 1982.

[2] Planted May 1978 on 40-inch (1 m) beds with 2 rows per bed; plant spacing 14 inches (0.35 m). Harvested 1980, 1981, and 1982.

Note:

a) To change pounds per acre to kg per hectare multiply by 1.12.

b) Rubber and resin contents in Tables 1-4 were obtained from whole plants including leaves by the liquid nitrogen method (Garrot et al, 1981).

Table 3. Average accumulation of biomass, resins, and rubber from five guayule varieties, harvested monthly; planted[1] November 1981, Tucson, Arizona. (Rubis, 1984).

Date of Harvest	Fresh Weight Lbs/A	Moisture %	Dry Weight, Lbs/A	Resins %	Resins Lbs/A	Rubber %	Rubber Lbs/A
3-17-83	21,020	53.0	9,840	7.83	765	5.53	545
4-19-83	24,090	56.2	10,585	7.43	785	4.70	500
5-23-83	35,700	59.8	14,245	6.98	995	3.56	505
6-16-83	45,415	58.6	18,785	6.42	1,205	3.28	620
7-15-83	47,810	60.8	18,690	6.52	1,215	3.29	610
8-25-83	45,935	59.2	18,785	7.20	1,355	3.14	590
9-16-83	39.030	50.9	19,065	6.74	1,275	2.65	505
10-17-83	40,120	54.0	18,505	5.83	1,085	2.91	540
11-15-83	41,890	49.5	21,135	6.63	1,405	2.63	560
12-19-83	37,905	45.0	20,780	5.48	1,155	2.88	595
1-16-84	36,525	42.6	20,925	5.39	1,135	3.03	635
2-15-84	33,120	39.9	19,790	6.24	1,245	4.14	820
3-16-84	32,070	40.5	19,010	6.51	1,240	5.00	955
4-17-84	35,890	44.9	19,745	6.79	1,355	5.03	960

[1] Planted 1 row per bed on 27-inch (0.68 m) beds; plant spacing 14 inches (0.35 m).

V. Variety Improvement

A. Variety needs

Higher rubber percentages and increased yields or a shorter production period are necessary to improve production economics. Processing economics would also be improved by higher rubber percentages. Higher yielding strains, higher rubber percentage or faster maturing lines can be obtained directly by selection from introductions and varieties; however, the main improvement will be made through a breeding program.

Potential areas for guayule production could be expanded if varieties tolerant to temperatures of 0°F-10°F (-17°- -12°C) were available. Mariola (P. incanum) a native to Arizona, survives cold temperatures and readily crosses with guayule. It may be used to improve frost tolerance.

If harvesting by clipping becomes an established production practice, then it will be necessary to have plant types that rapidly regrow after clipping. Plant types that grow erect are more adapted to clipping than short bushy plants.

B. Breeding and genetics

Triploid and tetraploid guayule breeding lines have a 70-100 percent apomictic breeding behavior. Apomictic plants have flowers which produce viable seeds without having been fertilized. In the vast native population in Texas and Mexico, guayule is an apomictic tretraploid with 72 chromosomes. In a small area in the state of Durango, Mexico, 36-chromosome sexual diploids have been found which breed sexually. In most native stands guayule and mariola grow together with some intercrossing taking place. Since mariola produces very little rubber, guayule that is introgressed with mariola is usually much lower in rubber content. Therefore, a bulk collection of guayule seed from native stands usually will produce a population of guayule much lower in rubber than selected lines. Such seeds are valuable for a breeding and selection program.

Important species related to guayule include P. bipinnatifidum, P. confertum, P. fruticosum, P. hysteropherus, P. incanum, P. lozanianum, P. schotti, P. stromonium, and P. tomentosum. All of these species cross readily with guayule and in a long term program are valuable as possible sources of favorable plant type, disease resistance, insect resistance, frost tolerance and many other characteristics.

Crosses among triploid and tetraploid guayule selections can be made per se, but at a very low percentage rate because of the apomictic characteristics of such plants. However, crossing can be facilitated through the use of 36-chromosome sexual diploids or 36-chromosome unreduced polyhaploids. Such a crossing program is in progress. Because of the apomictic nature of triploid and tetraploid guayule, F_1 plants, which are predominately self-reproducing, can be immediately tested as new lines.

C. Rubber analysis

The most important evaluation of guayule selections and varieties is the rubber content. At The University of Arizona, the liquid nitrogen method (Garrot et al) was developed as a relatively rapid and accurate method of analysis. This method also simulates what would be obtained by a rubber processing facility. The method is a double solvent extraction process in which the acetone extracts are mostly resins and the hexane extracts are long-chain rubber. Actual rubber is obtained from the analysis and it can be further tested for rubber quality.

VI. Production Practices

A. Land preparation

Adequate soil preparation before planting is very important if guayule is to be grown for 3-5 years before final harvesting. Fields should be subsoiled or chiseled to a depth of 25 inches (0.6 m) or more to break up soil compaction and allow deep rooting and moisture penetration, because compacted soils have greatly reduced root penetration, growth, and rubber production. Final seedbed preparation includes application of fertilizers and herbicides, then disking and forming beds.

The irrigation method greatly influences land preparation. If furrow irrigation is used for establishment, land planing or laser leveling is necessary to assure water control for maximum stand. If sprinkling is used for establishment only, land leveling is not as critical. Methods other than furrow irrigation should be considered if undeveloped land is to be planted to guayule.

B. Plant population and spacing

Plant populations between 10,000-20,000 plants per acre (25,000-50,000 plants per hectare) are being evaluated for rubber yield. These populations assume adequate irrigation or rainfall. If water is limited, lower plant populations may be advantageous.

Guayule has been planted with single rows on 27-, 30- and 40-inch (0.68-, 0.76- and 1 m) beds and double rows on 40-inch (1 m) beds. Plants were spaced 14 inches (0.35 m) apart in the row. The higher populations produced the most rubber in the shortest period of time but were more costly to establish. If clipping becomes feasible, the higher population should produce the highest rubber yield per acre. For seed production, single rows on 40-inch (1 m) beds have been used for machine harvesting and greatest seed increase from limited quantities of seeds.

A good stand is important for maximum rubber and seed production. Although plants bordering sites of missing plants have increased growth because of reduced competition, they seldom fully compensate for the loss. Since guayule is a perennial, such losses will affect each harvest.

C. Plant establishment

Securing a good stand is one of the major cultural problems for guayule growers in the Southwest. Because of slow growth, the seedlings may be hampered by excessive temperatures, seedling diseases, insect damage and competition from weeds. Plantings should be made in April or October to permit seedlings to develop a strong root system before experiencing the heat of summer or cold of winter. Seedlings from spring or fall plantings also are more competitive with common summer or winter annual weeds associated with stand establishment.

Three methods have been used for propagating and establishing field stands of guayule: (1) propagating transplants in a greenhouse; (2) propagating transplants in a field nursery; and (3) direct seeding of production fields. All three methods start with the use of seed.

1. Seed treatment

Guayule seed, like that of many desert plants, has a period of seed dormancy when harvested. Two types of seed dormancy have been identified: one is an inner seedcoat dormancy, which may last 12 months or longer; the second is an embryo dormancy, which may last 2 months or longer.

Seeds are usually treated for dormancy before planting. The best treatment for a particular seed lot may need to be determined through germination tests. The standard treatment is soaking with calcium hypochlorite or sodium hypochlorite (ordinary household bleach) using the following procedure: Seeds are first soaked in tap water for 4 hours to hydrate. A few drops of a wetting agent will help the process. Seeds are then soaked for 2 hours in a hypochlorite solution. The strength of the solution depends on the age of the seed:

a) Freshly harvested seeds	1.0% hypochlorite
b) 6-month-old seeds	0.5% hypochlorite
c) 1-year-or-older seeds	0.25% hypochlorite

After treatment the seeds are thoroughly washed and dried.

2. Propagation of seedlings in the greenhouse

Seeds are planted into compartmented trays and covered lightly with the planting mix. Seeds may be planted by hand or coated and planted with automatic tray planters. The seeds may be double-planted and thinned or they may be singly planted if the germination percentage is high. The trays should be placed in frames so they can drain freely.

One common planting tray is made of polystyrene with individual compartments, 1 inch (25 mm) square and 3 inches (76 mm) deep. A tray for an automatic transplanter has individual compartments 0.5 inch (13 mm) in diameter and 2 inches (50 mm) deep. Various types of rooting media have been used. The most common is a vermiculite-peat moss mix of equal volumes. For the automatic transplanter, the rooting medium is a synthetic plug that can be handled by the planter mechanism. Lime is added to the rooting medium or is added in the water to obtain a pH of 7.5-8.0. It is important that the growing medium be porous and drain well since young seedlings may succumb to seedling diseases in saturated media. Fertilizer is usually applied in the water. Seedlings have been grown successfully using an NPK mixture and Fe or using a complete fertilizer and minor elements.

Seedlings have grown best with greenhouse temperatures from 70°F-90°F. Guayule seeds germinate and grow best under high light intensities.

Seedlings may be large enough to transplant within five weeks or they may be held as long as a year. An automatic transplanter may transplant seedlings at about the 4- to 5-leaf stage; single-action manual transplanters require seedlings somewhat larger. Seedlings may be trimmed at about 6 weeks of age to a height of about 2 1/2 inches (60 mm) or just above the apical meristem. Trimming should continue every 3-4 weeks until the plants are at least 3-4 months of age. These seedlings are very strong, resulting in transplants with very high establishment rates.

Seedlings need to be hardened before transplanting. This may be accomplished by moving them outside or removing the top of the greenhouse. Trimming also is a very good hardening process.

3. Propagation of seedlings in field nurseries

Direct seeding in specially prepared fields was used during the ERP to propagate seedlings. Intensive care and management were necessary but vigorous plants were available for transplanting 6-8 months after seeding. The water and labor requirements were high but this method was less expensive than direct seeding of entire fields. Weed control also was a problem.

The plants produced in field nurseries may survive under more adverse conditions than greenhouse plants. Nursery plants are normally transplanted with bare roots and have survived for several weeks without water at transplanting if the tops are cut off. Field nurseries may be feasible today but mechanization for this system is less developed than for greenhouse propagation and would be more labor intensive.

4. Transplanting

Successful transplanting requires adequate soil preparation, proper temperatures and adequate irrigation after transplanting. Temperatures should be cool enough to prevent wilting of transplants before water can be applied and warm enough so that rooting will occur. Ideal temperatures are about 70°F-80°F (20°-27°C). In Arizona, transplanting is best accomplished in the spring during March, April, and May and in the fall during September, October, and November.

Transplanting has been accomplished with many types of machines. The most successful transplanters have positive action fingers that place the transplant at a specified depth. With some transplanters individual transplants are manually placed in the fingers. With semiautomatic transplanters, transplants are manually placed on chains that, in turn, feed the fingers. With completely automatic transplanters the transplant is never touched by the operator.

5. Direct seeding

Direct seeding of guayule has not been successful because of low survival and weed competition. It is expensive because seed costs are high due to limited availability. Adequate emergence can be obtained although it is slow and variable; however, seedling losses are high due to diseases, pests and wind damage. Best emergence has been obtained when seeds are planted very shallowly and barely covered with sand or vermiculite.

Direct seeding of bare seeds requires precision planters and a high seeding rate because germination and emergence rates are low. Coated seeds are easier to plant at desired rates. Coating is available commercially, unfortunately, some coatings seem to reduce germination.

Gel seeding of pregerminated seeds is being used for some vegetables. With this procedure seedling emergence occurs sooner after planting, but the gels harden and reduce emergence if they are allowed to dry.

D. Irrigation

1. Establishment

Irrigation is a critical factor during the establishment of guayule. Transplants have been established successfully using furrow, sprinkler, and trickle irrigation systems. Survival rates of 90-97 percent are possible with sprinkler and trickle irrigation while 60-90 percent survival rates occur with furrow irrigation. With any system the field should be irrigated so that moisture is available in the beds at transplanting. This should occur 2-4 weeks before transplanting so that the field surface will dry before there is traffic by transplanting equipment.

The management of the irrigation system should consider that transplants were grown in a greenhouse and have small root systems. Transplants need high moisture levels for approximately 10 days to initiate new rooting. Water should be applied immediately after transplanting. If water is not applied within a few hours, transplant survival will be greatly reduced. If furrow irrigation is used, the beds should be wet completely across the top during the first irrigation after transplanting. Light irrigations may be necessary every 2-5 days during the first 2 weeks, depending on temperature. Alternate furrow irrigation is suggested if the water is salty. Laser-leveled fields with small slopes are best to obtain high plant survival with furrow irrigation.

With sprinkler irrigation, best results will be obtained if the system is operated daily unless temperatures are cool and surface soil moisture is high. The first irrigation should wet the soil to a depth to contact with water remaining from the preirrigation. Subsequent irrigations should prevent plant wilting and keep the surface moist. As the plant roots begin to grow, irrigation frequency can be reduced. A solid set sprinkler system is most reliable. After the first 2 weeks, the plants should have started to take root and furrow irrigation can be used.

When direct seeding, the soil surface must be kept moist for about a week for seeds to germinate and emerge. Thus, sprinkler irrigation has a great advantage for direct seeding because the soil surface can be kept moist with less water than with furrow irrigation. After emergence many young seedlings die, probably as a result of insects and seedling diseases.

As the plants grow, irrigation frequency can be reduced. By the time the plants are 3 months of age, irrigations can be reduced to about once a month. During the first year 24-36 inches (600-900 mm) of water may be required.

2. Production

Once the plants are well established, four-six irrigations per year of 4-6 inches (100-150 mm) each will be sufficient. The estimated irrigation times are March, May, June, July and September. Recent studies in Arizona show more water will increase plant growth and increase total rubber production, but decrease the rubber percentage (Table 4). Unless the plant population is high, more than 36 inches (900 mm) of water per

Table 4. Effect of water from irrigation on guayule rubber yield and rubber content; planted[1] April 1980, Litchfield Park, Arizona. Harvested March 1983.

Water applied Yearly, inches	Rubber Percentage	Rubber Yield lbs/A
36	4.61	1360
28	4.30	820
20	5.15	1160
12	5.91	920

[1] Planted on 40-inch (1 m) beds with 2 rows per bed; plant spacing 14 inches (0.35 m).

year may decrease rubber production.

Guayule may have potential in a farm-cropping pattern because it can survive during the summer with minimum water. Therefore, water would be available to meet the peak needs of other crops and guayule would provide an alternative use for otherwise idle land.

E. Weed control

Weeds may be a major problem in guayule. Until herbicide programs are available, it will be necessary to control weeds in guayule by hand and with mechanical cultivation with good management. Weed problems during establishment can be reduced by irrigation before planting (to germinate weed seeds) then cultivating. Sprinkler irrigation has been particularly effective for this practice; however, sprinkler irrigation for establishment produces more weeds on the beds than furrow irrigation. Weeds on the beds are harder to control than in the furrows. A good stand of guayule will reduce weed problems after the first year.

A serious problem has been winter annual weeds, such as, London rocket, little mallow, prickly lettuce, spiny sowthistle and wild turnip. If guayule is planted in the fall, these weeds grow rapidly while guayule is dormant. In new plantings, weeds must be removed from the plant row by hoeing, since pulling the weeds may pull the transplants.

Summer annual weeds (Palmer amaranth, Wright groundcherry, horse purslane, junglerice and barnyard grass) could be a greater problem than winter weeds. Many of these weeds have been selectively controlled in experimental spring plantings by soil applications of herbicides not yet registered for use in guayule. Annual weeds will be a major problem in the first year after planting.

When annual weeds are controlled by hand, mechanical cultivation or herbicides, perennial weeds such as Bermuda grass, Johnson grass, and silverleaf nightshade will remain. Many perennial weeds have been controlled in research plots by spot applications of glyphosate but it is not registered for this use.

In the second, third, and fourth years after planting, trees and shrubs are a major weed problem. Mesquite, palo verde, and desert-broom plants may need to be removed by hoeing.

Weed problems in guayule can be reduced by selecting fields that have had few weeds and by planting in the spring when the crop will grow most rapidly. Frequent irrigations after guayule is planted increases weed growth and prevents mechanical culivation. Mechanical cultivation is possible for the first two years after guayule is established.

Guayule production will be difficult until herbicides are registered for use in this crop. Diuron, fluridone, glyphosate, oxyfluorfen, pendimethalin, trifluralin and Bas 9052 have shown promise for use in guayule. Until some of these herbicides receive state and/or federal registration for use in guayule, hand hoeing and cultivation must be used for weed control.

F. Soil nutrients and soil salinity

1. Fertilizer

During the ERP, guayule showed little response to fertilizer but it was grown mostly in soils having good fertility. Response to nitrogen was most noted where soils had low fertility levels. In current tests guayule has shown some response to fertilizers, mostly nitrogen and calcium.

Seedlings in the greenhouse have shown good growth when nutrient solutions of only NPK have been added to the water; however, Ca and Fe are also commonly added. These nutrients should be applied on a regular basis to promote strong seedlings. Yellowing of the leaves usually indicates the need for nitrogen.

2. Soil salinity

Guayule is considered only somewhat salt tolerant; however, only limited information is available. In general, salinity decreases germination and seedling growth. Mature plants apparently are more salt tolerant; good growth was obtained in fields irrigated with saline water during the ERP.

3. Mycorrhizal fungi

Research carried out during the ERP indicated that deficiencies of phosphorus, nitrogen and several other minerals could limit productivity of guayule. In recent greenhouse studies, several mycorrhizal fungal species in the genus Glomus have increased phosphorus uptake in inoculated guayule seedlings and resulted in a 2- to 3-fold increase in total dry weight of 3-month-old plants compared to non-inoculated controls.

Field trials using mycorrhizal fungi showed greater concentrations of calcium, magnesium and zinc in inoculated plants. Inoculated plants also showed significantly higher rubber percentages at 12 and 18 months than non-inoculated plants.

G. Diseases of guayule

Approximately 20 pathogens of guayule are known; the most important of these are associated with soils. Recent isolations from "distressed" greenhouse or field plants in Arizona include Fusarium spp, Rhizoctonia Solani, Phytophthora spp, Pythium spp, Macrophomina phaseolina and Verticillium dahliae. Fusarium and Rhizoctonia have been encountered most frequently.

Pathogens can be divided conveniently into two groups: those affecting stand establishment and those associated with mature plants. The more important problems are noted here.

Poor stand establishment: Species of Fusarium, Phytophthora, Pythium, and Rhizoctonia can destroy seeds and emerging seedlings. Plants that survive infections may remain stunted and non-thrifty in appearance.

Excess water, soils with high organic matter and poor drainage favor infection in the field. Losses also can occur in the greenhouse when planting containers are reused; these should first be thoroughly washed in a solution of 10 percent household bleach or sterilized by other means. Potting soils should be pasteurized. Currently, selected chemicals are being tested for possible use as protective seed-treatments and soil-drenches.

Workers in the ERP also observed losses of guayule up to 4-6 weeks of age as a consequence of soil being splashed onto plants by overhead sprinklers.

Diseases of established plants: Older seedlings of guayule and mature plants are susceptible to a number of pathogens, most of which attack the plant roots and crown. These include:

1. Phymatotrichum omnivorum (Texas root rot). Typically, guayule plants infected in mid-summer will suddenly partially or completely wilt. Roots will be brownish in color; cortical tissues generally are easily sloughed. Severely affected guayule will die soon. Plants in frequently irrigated, heavy soils are most prone to infection. There are no economically effective methods of eradicating this fungus.

2. Verticillium dahliae (Verticillium wilt). Symptoms are best seen when temperatures are moderate. In guayule, symptoms first appear on the lower leaves, then the upper leaves. Usually, one side of the leaf blade becomes yellow first. Affected tissues may dry out and leaves also may be twisted. Plants with foliar symptoms always show a browning of some or all of the xylem. Very susceptible plants will die but some plants with severe initial symptoms survive and produce new but stunted growth. Other plants with vascular discoloration may develop only mild leaf symptoms. Currently, the best control of Verticillium wilt is to grow guayule in non-infested soils and to plant such lines as 11605 and 4265XF which show some tolerance to this pathogen.

3. Macrophomina phaseolina (Charcoal rot). Symptoms induced in guayule by M. phaseolina are best seen when plants are subjected to high temperatures and water stress. Wilting and then death of aerial plant parts will occur. Roots will have dark-brown sunken lesions; internally, such roots will appear dark. Typically, minute black sclerotia form on dead root and stem tissues. These facilitate diagnosis. The incidence of charcoal rot of guayule has been reported to be reduced by frequent irrigations and at least delayed by close (under 12 inches or 0.3 m)spacing of plants in beds.

4. Phytophthora drechsleri. Phytophthora root and crown rot was noted in most areas where guayule was planted during the ERP. P. drechsleri is similar to M. phaseolina in being favored by higher summer temperatures; it is dissimilar, however, in that infection is dependent upon soils being saturated or nearly saturated with water for 18 hours or more. Under such conditions, plants suddenly wilt and die. Root lesions generally are 1-4 inches (25-100 mm) long, dark and sunken. Tissues beneath the lesion also may be dark. Infections typically occur on roots several inches below the soil surface.

5. Phythium ultimum (Pythium root rot; pink root rot). In addition to causing root and stem infections in emerging plants, P. ultimum also infects the roots and crowns of older seedlings through about 4 months of age. Cool to moderate temperatures and abundant moisture are most favorable for this fungus. The first symptom is premature wilting during midday heat. Severely affected plants will die suddenly. A pinkish or reddish color of the wood is usually associated with infection sites, particularly those involving the tap root; but the color disappears on exposure to air. As with Phytophthora drechsleri, lesions usually occur at depths of several inches. Crown infections occur when soil is thrown onto plants (as in the course of various cultural practices) which then are exposed to 4-6 hours of sprinkler irrigation or to foggy weather. Disease is minimal in soils with good drainage and when irrigations are well regulated.

6. Cuscuta spp. (Dodder). Dodder can parasitize guayule, complicating harvest of seeds and shoots. This pathogen is easily recognized by its slender, limber, yellowish stems that can rapidly cover guayule plants. Infected guayule plants should be eradicated promptly.

Other pathogens of established guayule that were of local or sporadic importance include: Erwinia chrysanthemi (previously named E. carotovora f. sp. parthenii) (bacterial root and stem rot) in the San Joaquin Valley, California; Sclerotinia sclerotiorum and S. minor (Sclorotinia root rot) in California and Arizona; Diplodia threobromae (Diplodia die-back) in southern Texas; and Sclerotium rolfsii (southern root rot) in Arizona and Texas.

H. Insects

The insects found in guayule in Arizona, like those occurring in other crops, are a mixture of harmless, beneficial and damaging (plant-feeding) species. The beneficials include honey producers and/or pollinators such as domestic or native bees. Other beneficial species include predaceous or parasitic species that feed on other insects and keep the plant-feeding types in check.

More than 30 phytophagous species of insects and mites have been collected from guayule. The importance of some of these species depends on the purpose for which the guayule is being grown. For example, an infestation of lygus bugs would pose a greater threat in a field being grown for seed production than in one intended for rubber production, since these insects preferentially feed on fruiting structures such as floral buds and developing seeds and consequently can severely reduce the viability of guayule seeds.

Defoliation ("shot-holing") of leaves by flea beetles (Systena sp. and Epitrix sp.) was observed in some fields of transplanted guayule in central Arizona in 1980 and 1981; it resulted in 10 percent plant loss. Special permission was obtained to apply chemicals for control. Several other phytophagous species occurring in Arizona were previously reported as occasional pests of guayule by USDA entomologists during the ERP. These insects include the green peach aphid (Myzus persicae [Sulzer]); the cotton (or melon) aphid (Aphis gossypii [Glover]); lygus bugs (Lygus hesperus [Knight]) and (L. elisus [Van Duzee]); the carrot beetle (Bothynus gibbosus [DeGeer]); and the migratory grasshopper (Melanoplus sanguinipes [Fabricius]).

Both ERP studies and more recent observations suggest that established (1 year or older) stands of guayule are less vulnerable to serious insect damage than seedlings or recent transplants.

VII. Seed Production

A. Field management

Guayule grown for seed production is not necessarily managed in the same way as guayule grown for rubber production. It may differ in row and plant spacing, amount and scheduling of irrigations, fertilizer applications and insect control. In Arizona the best seed production is during spring and fall. Seeds produced during the hot summer months are usually poorly filled and are of poor quality.

Because flowering is a response to active growth (each new branch terminates in a flowering stalk), the irrigation applications need to be scheduled to bring on growth at the correct time. In the spring a heavy irrigation is normally applied during early March, which will bring on flowering in April and May and seed maturation during May and early June. Additional light irrigations usually will be needed during seed set. For fall seed production, an irrigation should be applied during late August or early September. Heavy irrigations and standing water may be conducive to root rot during periods of extremely high temperatures. Therefore, irrigations during August and September should be managed to prevent standing water.

Fertilizer applications increase rubber production in some instances, because of more vegetative growth and larger plants increased seed production also has been obtained. During seed stockpiling in 1950, both nitrogen and phosphorus were recommended at rates of 50 pounds per acre (55 kg per hectare) of actual N and P. Preliminary research indicates that calcium also may be beneficial.

Plants 2 years of age and older are difficult to machine harvest for seed because of large plant size. Current research indicates that seed harvest efficiency may be improved by mechanically trimming the plants like a hedge. The new growth has more seed heads at a uniform height for easier harvest.

B. Harvesting and cleaning seed

Mechanical seed harvesters are custom designed, usually to a specified row width and sometimes to a certain plant height. Most harvesters are built on the principle of air suction, with a small amount of manipulation for gathering the seed. Since seeds do not ripen uniformly, new seed is available for harvest about every 10-14 days. Because wind and rain can easily shatter seed from the plant, the timing of harvesting is very critical.

Seeds are harvested as part of the ray floret complex and must be processed by threshing and cleaning. Threshing is usually accomplished by a gentle rubbing action using a seed huller or a scarifier. One machine used is a burr clover huller, consisting of a rubber-covered, conical-shaped rotor turning inside a rubber-lined drum. A scarifier removes the hull or other parts from the seed by whirling the seed inside a drum that has a rough carborundum wall.

After threshing, good seeds are separated from chaff and fine plant parts with a seed separator, which consists of a series of sieves and an air blower. Next, seeds are cleaned with a vibrating gravity cleaner to remove plant parts that are about the same size and weight as the seeds. This machine also separates seeds into quality categories according to seed density. Seeds also can be separated into density categories using hexane, acetone or water, but such seeds lose storage quality. The final quality of the seed is determined by germination and vigor tests.

C. Seed certification

Seed certification criteria have been developed. Seed grown under an official certification program are certified for isolation, variety, purity and germination. Seed certification attests to the genetic purity of the variety but does not attest to its yield or rubber content. However, only varieties that have shown good performance or that have some special value are generally entered into a certification program.

VIII. Rubber Harvesting and Processing

A. Harvesting for rubber.

During the ERP guayule was harvested by undercutting plants, which then were partially dried in the field, and later baled and stored near the processing plant. Since guayule lacks an antioxidant, the rubber quality may deteriorate during handling, baling, chopping or storage.

Therefore, guayule should be processed shortly after harvesting.

An alternative harvest method currently being studied is to clip the plants 2-4 inches (5-10 cm) above the ground and leave the stubble for regrowth. The new shoots of a clipped plant grow more vigorously than a new transplant because of the established root system, and nearly attain the size of 2-year-old plants in 1 year. The main advantage of clipping is a reduction in expense and time of replanting.

The best time to harvest appears to be when the plants are dormant. This is particularly true if plants are clipped. The rubber content is probably highest during dormancy and the cooler temperatures may reduce rubber deterioration. However, seasonal harvesting will increase processing costs. An efficient harvesting-processing system needs to be developed.

B. Methods of processing

Since guayule rubber is found in small individual cells in the branches, stems and roots, the whole shrub must be processed. Two extraction methods are being considered for commercialization. One process consists of a Bauer wood pulping mill, which is used by the Mexican pilot plant at Saltillo, Coahuila. The other method is a direct solvent process developed by the Firestone Tire and Rubber Company.

The Mexican pilot plant has the capacity for processing one ton (1,000 kg) of shrub per day. Briefly, the process is as follows: The shrubs are parboiled in hot water to coagulate rubber in the small cells and to remove leaves; the plants are coarsely ground in a hammer mill and pulped in a Bauer mill, using a water solution with caustic soda to break open the small rubber-filled cells. The resulting mass subsequently is passed through two large slurry tanks where the bagasse sinks and the rubber "worms" are skimmed from the surface. The rubber-resinous worms are rinsed in water to remove the caustic soda and the resin is removed from the rubber using warm acetone with a fluid-bed process.

A direct solvent process is being evaluated by Firestone as a laboratory model that can process a few hundred pounds of shrub a day. Briefly, this process is as follows: the shrub is parboiled and trammeled to remove leaves; the shrub is dried, ground and extracted with acetone to dissolve resins. The acetone and resins are removed and the rubber is extracted from the remaining material with hexane. The rubber is water coagulated, steam stripped, screened, dried and baled. Although the direct solvent process has not been tested on a large scale, it is preferable to the Bauer mill process because it uses less water. The solvents are recovered and recycled.

C. By-products

The by-products of guayule having potential economic value are wax, resins, cork, fiber and bagasse. They have not been commercially utilized so their composition and commercial potential is mostly unknown. From laboratory analyses it appears they could be of considerable economic significance and probably could cover the cost of processing the rubber. There are many possible uses for the by-products, including the bagasse, which could furnish sufficient energy to operate the processing facility. By-product availability and composition will depend on the processing method used. For example, the resins in the Firestone extraction method would contain the water solubles, whereas those in the Mexican process would not.

IX. Economics and Marketing

A. Production costs

There is little commercial experience upon which to rely in developing cost budgets for guayule since commercial plantings in Arizona total less than 250 acres. Production practices were assumed based on current guayule research, ERP practices, experience of commercial growers and typical farm operations used today. As better practices are developed, production costs will change. Maricopa and Pinal counties in central Arizona were selected as representative locations for estimating production costs using 1983 values.

A list of field operations was projected (Table 5) for each year assuming planting occurred in April of Year 1 and harvesting occurred at the end of Year 3. Labor costs are included in each operation. It was assumed that 36 inches (910 mm) of water would be needed the first year for establishment and growth and 24 inches (610 mm) each for Years 2 and 3. Furrow irrigation for establishment and growth is assumed on a laser-leveled field, but depending on field conditions, a sprinkler system may be needed to assure good plant survival. It is assumed that approved chemicals will be available for weed control. At the end of Year 3 the plants will be dug, chopped and hauled to a processing plant.

Procedures for plant establishment on a commercial basis are uncertain and probably a major cost. For Table 5 it was assumed that 15,000 transplants per acre (37,200 per ha) would cost 3 cents each, including transplanting. The total projected cost of growing an acre of guayule using an interest rate of 12 percent is $2,480 per acre. If transplant costs were 7 cents each, the growing costs would increase by about $753 to $3,233 per acre.

Direct seeding costs for other small seeded crops are typically less than the $450 per acre assumed for transplanting. Since guayule seed costs are high and seedling survival is low, direct seeding costs for guayule may not differ from costs for using transplants. Irrigation costs would increase because a sprinkler system would probably be necessary for germination and early plant growth, and weed control costs also may increase.

Yields of rubber have only been measured from small experimental plots (Tables 1-4). It appears that rubber yields at the end of 3 years could vary between 1,200 and 2,400 pounds per acre. Using these projected values, the growing cost of rubber could easily vary between $1 and $2

Table 5. Projected per acre costs for growing guayule in Central Arizona based on assumed production practices.

	Years 1	2	3
Establish Stand			
Rip or subsoil	$20		
Disk	11		
Laser level	30		
Fertilizer 100#N 50#P	42		
Herbicide	15		
Disk	6		
List rows and buck ends	8		
Preirrigate (12 in)	44		
Mulch beds	6		
Seedlings & transplantings (15,000)	450		
Irrigate (3X) (6 in)	22		
Sub Total	654		
Growing Costs			
Cultivate (3X)	24	24	24
Disk ends (3X)	3	3	3
Buck rows (3X)	3	3	3
Irrigate (4X)(18 in)	66	88(24 in)	88
Herbicide	15	15	15
Hand Weed (2X)	60	60	60
Insect Control	12	12	12
Management	35	35	35
General Farm Maintenance	40	40	40
Production Credit (12%)	72	15	15
Interest on Previous Credit	0	118	167
Sub Total	330	413	462
Harvesting & Hauling Costs	0	0	150
Fixed/Overhead Costs			
Taxes	13	13	13
Insurance	10	10	10
Wells @ $21/AF	63	42	42
Irrigation System (ditches)	10	10	10
Land	75	75	75
Sub Total	171	150	150
Total Annual Costs	$1155	$563	$762
Total Costs	$1155	$1718	$2480

Table 6. Projected cost of producing rubber from guayule in Arizona using a range of yields and growing costs for a 3-year production cycle.

Yield pounds/acre	Growing costs, $/acre $2480 Cost per pound, $	 $3233
1200	2.07	2.69
1800	1.38	1.80
2400	1.03	1.35

per pound (Table 6).

Data are not available to project reliable production costs for a harvesting system that includes clipping. However, several factors in a clipping system indicate production costs could be reduced. First, establishment costs would be prorated over a longer period. Second, rubber yield is likely to be increased by clipping. Finally, harvesting would begin in the first or second years rather than the third year so that income would be received earlier. Harvesting costs would be increased and offset some of the other advantages.

B. Marketing

Marketing includes all functions that occur in the process of getting a product from a producer to the final consumer. The rubber from guayule is nearly identical in microstructure to Hevea natural rubber and has comparable properties. From an economic standpoint, guayule and Hevea natural rubber should be considered as functionally interchangeable. Thus, the market for guayule rubber is the same as that for Hevea rubber, and the price of guayule rubber in the market system must be competitive with Hevea if it is to be used by manufacturers. It should be noted that all guayule grown in the United States since World War II has been for research purposes. Marketing has not been a consideration.

The historical competition between natural and synthetic elastomers in the United States has been similar to that of the world rubber market. Since 1965 the average use of NR (natural rubber) in the United States has never accounted for more than 25 percent of the total annual elastomer consumption. Rubber consumption increased rapidly in the United States during the 1960s, particularly SR (synthetic rubber) consumption, which grew at an annual rate of 8 percent between 1961 and 1968 compared with a 2.9 percent increase in the use of NR during the same period. The 1974-1976 recession in rubber consumption affected the growth of SR consumption more than that of NR. Several factors account for this: this period reflects the impacts of the Arab oil embargo and the resulting rise in SR feedstock prices; the rising popularity of radial tires has made NR demand more stable; and interchangeable NR/SR use is primarily occupied by SR, i.e., there is room for significant expansion of NR into more of these uses, but not for SR.

Based on projected growth rates of total rubber demand and NR's share of the market in the late 1970s, the rubber industry was projecting a natural rubber shortfall commencing early in the 1980s. These projections, however, were based on all-time-high conditions in both rubber demand and price. In early 1980, the price per pound of RSS-1 NR briefly exceeded $0.80 on the New York commodities exchange (Wall Street Journal). The recession of the early 1980s greatly changed the demand and price picture for natural rubber. By the third quarter of 1980, world demand for natural rubber was declining and by September 1981 the price of RSS-1 had fallen to $0.48 per pound, a drop of about 46 percent in 1.5 years. NR prices continued to decline to approximately $0.45 per pound and remained relatively stable at that level for several years. By late 1983, NR began a slow recovery. The Wall Street Journal for Friday, January 13, 1984, reported NR prices at $0.575 per pound, a year earlier they had been at $0.4425.

Projecting future prices for guayule rubber depends upon the full range of production costs, including farming production and processing, plus transportation and marketing. The weakest link in this chain is projection of processing costs. In the early 1980s, processing costs were estimated to be roughly offset by by-product values -- resins, waxes, bagasse. However, these processing costs were based only on analogy to synthetic rubber production facilities, not an analysis or extrapolation from pilot guayule processing facilities; the latter do not currently exist in the United States. Analyzing processing costs and integrating those into an overall guayule production economics is a top priority research need.

At present, the market potential for guayule rubber cannot be accurately assessed. If processing costs and by-product credit were again assumed to balance, agricultural production costs (Tables 5 and 6) would not allow entry of guayule rubber into the NR market at this time. The low range of production costs, assuming $0.03 per plant for transplanting, run from $1.03-$2.07 per pound of rubber. The lowest figure represents nearly twice the product market value of $0.575 per pound of NR.

The entry of guayule into the rubber market depends upon the total of production, processing, transportation and marketing costs (including profit) matching world natural rubber prices, or upon government subsidies.

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