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AN ESTIMATE OF THE MAXIMUM SUSTAINABLE YIELD FROM HARVEST OF GUAYULE WILDSTANDS IN THE VICINITY OF CEDROS

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PREFACE

In 1980, IIASA joined together with the Centro de Investigacion en Quimica Aplicada (CIQA) to study resource development alternatives for arid and semi-arid regions. This joint effort is motivated by the perception that planning and programming of development projects, as they typically are applied to projects for drylands, are inadequate and pose serious obstacles to successful development of these regions.

Two characteristics distinguish the problem of planning and programming development projects for drylands. First, all of the common difficulties that beset development planning and programming (e.g., inadequate data, importance of poorly understood social and cultural relations, inadequate infrastructure, inadequate organizational capacity) are present in the extreme. Second, even very modest-sized development projects are usually enormous in relation to the social, economic, and technical structure of drylands regions; their ramifications are little short of revolutionary.

To focus our efforts to improve planning and programming methodologies for dryland regions, it was decided to examine a specific problem: the prospects for developing a dryland region in northern Mexico based on the exploitation of 6 vegetal resources native to the region. A description of this effort is available in

> Anderson, R.J., E. Campos-Lopez, and D. Gourmelon. An Analysis of Renewable Resource Development Alternatives for the Northern Arid Region of Mexico: Study Prospectus. WP 81-7. International Institute for Applied Systems Analysis. (January, 1981).

Guayule (parthenium argentatum gray) is one of the vegetal resources under investigation in this study. Guayule shrub, which grows wild on the sierras of the Chihuahuan desert, produces a high molecular weight hydrocarbon that can be processed into a premium-quality natural rubber. For approximately 50 years during the first half of this century a small but important guayule rubber industry operated in Mexico.

The Mexican government currently plans to reactivate the guayule rubber industry using shrub harvested from wildstands as the basic source of shrub. This paper examines a critical aspect of this plan, the limits on the amount of shrub that can be harvested without exhaustion of the wildstands and without reforestation or other forestry management methods.

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None of these kind individuals is to be held accountable for any errors, ambiguities, or other faults that may remain.

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1 INTRODUCTION

In his prologue to a compendium of papers on guayule (partnenium argentatum, gray), Campos-Lopez (1978) eloquently recounts the history of Cedros, a small town in the Chihuahuan Desert of Mexico. While Cedros was settled by the Spanish, the town in roughly its present form, he notes, dates to the early 1920's, when the Continental-Mexican Rubber Company began operating a plant to extract rubber from guayule shrub collected from stands growing wild on the surrounding sierras.

The plant in Cedros was one of 19 that operated at one time or another in the Chihuahuan Desert during the first half of the 20th century, and one of three operating during World War II. Until the late 1940's, the Mexican guayule rubber industry's fortunes waxed and waned with prices on the international market for rubber. During World War II, with the interruption of supplies of hevea rubber from Southeast Asia, guayule production boomed. Over 43 thousand metric tons of rubber were produced from guayule shrub harvested from wildstands in Mexico between 1940 and 1945.

Shortly after the conclusion of the war, guayule rubber production in Mexico collapsed. The collapse of the social structures in small towns like Cedros, which were built upon the operations of this industry, was equally swift. Those who could left Cedros, some for the emerging industrial cities of Mexico, and some for other perceived opportunities. Those who remained eke out an existence based upon subsistence agriculture, animal husbandry, and harvest of lechuguilla (from which fiber is extracted) and candelilla (from which wax is extracted). Many await an opportunity to leave.

Most observers attribute the demise of Cedros and the Mexican guayule rubber industry to the reduced demand for guayule rubber brought about by a resumption of flows of hevea rubber from Southeast Asia, and by the rapid, almost incredible, emergence of synthetic rubber substitutes for natural rubber. The importance of these factors certainly is not to be denigrated. World market natural rubber prices did plunge at the conclusion of the war and, in real terms, continued to fall during most of the postwar period.

But there is more than this to the demise of Cedros. All available evidence points to the conclusion that the standing crop of guayule had been severely depleted by the high harvest rates of the 1940s. Even if demand had not collapsed, a drastic and prolonged curtailment of production almost certainly was inevitable.

The story of Cedros typifies what has happened at many other times and in many other places: excessive use of natural resources that are, in principle, renewable has depleted them, both in quantity and quality, and resulted in the temporary cessation or complete abandonment of economic activity based upon their use, with consequent severe social and economic disruption. Well-known cases include the 1973 collapse of the Peruvian anchovy fishery, the extinction of certain large mammals in North America, and rampant overgrazing of rangelands in many nations today.

At the root of exhaustion of renewable natural resources is exploitation at rates in excess of the productivity of the resource. Excessive exploitation rates may occur for many reasons. Somestimes, there are strong economic incentives which make it individually rational (on a pure profit and loss basis) to exploit renewable resources at ruinous rates. Many times, however, ruin comes as a surprise when some unknown and perhaps even unanticipated limit to production is reached. It is not easy in most instances to estimate the productive limits of renewable resources. Data frequently are poor, and underlying bionomic processes usually are only partially understood.

This paper examines the sustainable yields from harvest of guayule wildstands (i.e. natural stands not subjected to any form of cultivation) in the vicinity of Cedros. Such analysis is of more than academic interest. The Mexican government has recently announced plans to produce guayule rubber using (at least initially) guayule shrub narvested from wildstands. According to preliminary plans, the first plant is to produce 5 thousand metric tons of rubber per year, to be located in Cedros, and to be supported by shrub harvested from wildstands within a 130 kilometer radius of Cedros.

Can this level of production be sustained? Or will Cedros flourish briefly, to wilt once again when the standing stock of harvestable shrub is depleted? What level of production could be sustained?

These are real and pressing questions for the redevelopment of the Cedros area, and it is hoped that this paper contributes to answering them. It must be stressed that the estimates developed below are based upon interpretation of currently available data. These data are both few in number and sometimes conflicting. Accordingly, the reader should keep firmly in mind that the estimates presented here are tentative. It is entirely possible that new data will make it necessary to revise them.

Subject to the above caveat, the analysis in this paper will show that the maximum sustainable annual harvest from guayule wildstands in an area enclosed by a circle centered at Cedros with a radius of 130 km, is about 30 thousand metric tons.

This estimate is somewhat lower than another tentative estimate (i.e. 150 thousand tons) that has been advanced by Foster et al (1980). Moreover, it is well below the level of sustainable yield that would be required--under current conditions--to support an annual production of 5 thousand metric tons of rubber. Depending upon the precise figures for rubber content of shrub (dry weight basis), the difference between dry weight and field weight (e.g. due to leaves, water, losses during harvest and transport from field to factory), and the processing efficiency of rubber extraction, a sustainable yield of 100 thousand metric tons of shrub (field weight) could be required to support sustained production of 5 thousand metric tons of rubber per year.

The plan of the paper is as follows. In Section 2, a model is presented for estimating the sustainable yield of harvest from guayule wildstands. The model chosen is one of the simplest possible for this purpose. While there are some objections that can be raised to the application I shall make of this model (these objections are also considered briefly in this paper), the model seems to be adequate to the purpose for which it is used.

Section 3 examines the data available to estimate the model. As will become clear, there is relatively little data on which to base estimates of the model's parameters. Moveover, there are seeming inconsistencies in some of the data, and ambiguities concerning the compatibility of data taken from different sources. While some effort is made in this paper to reconcile existing data, much more needs to be done in this area.

Section 4 presents alternative estimates of the parameters of the model adopted here. Calculations of maximum sustainable yields based on these parameter estimates are also presented. As noted above, my estimates imply a maximum sustainable yield of approximately 30 thousand tons of shrub per year. This section also reports some additional supporting evidence for these estimates of maximum sustainable yield drawn from the history of guayule exploitation in Mexico over the first half of the 20th century.

In Section 5, some approximate estimates of the ability of guayule wildstands to support sustained production of 5 thousand tons per year of rubber are reported. It is doubtful, given my estimates of the sustainable yield of wildstand harvest, that this level of production could be sustained using only shrub harvested from wildstands. Rough calculations suggest that a rubber production of 5 thousand tons per year would virtually exhaust guayule wildstands within <u>eight</u> years. Of course, if these estimates are correct, production probably would come to a halt for economic reasons (i.e. due to the extreme expense of harvesting shrub) well before guayule wildstands were completely exhausted.

In Section 6, a number of carefully qualified conclusions are offered. It is certainly premature to conclude that my estimate of sustainable harvest is correct. While I firmly believe that the estimates presented nere will turn out to be near the mark, it is clear that a definitive estimate must await additional research. The concluding section comments on the research that is needed.

2 A BASIC MODEL

The point of departure for the present analysis is one of the simplest possible models of biomass accumulation, the logistic model of population growth. Several objections can be raised to this model, both in its most usual applications to the study of populations of motile organisms in an environment small enough for any organism to be likely to move freely throughout the whole of it, and to my application of it to a population of sedentary organisms--the guayule shrub--that are distributed in clusters. Some of these objections are dealt with later in this section. For the moment, let us hold them in abeyance.

The logistic model of biomass accumulation holds that the rate of mass accumulation may be approximated as a quadratic function of the stock of biomass. That is, the rate of accumulation is density dependent, with the rate declining continuously with increasing density. Letting S(t) denote the stock of a certain type of biomass at time t and s(t) denote its continuous time rate of change, the logistic model of biomass accumulation may be written as

$$(1) \qquad s(t) = rS(t)\left[1 - \frac{S(t)}{K}\right]$$

where r is a parameter known as the <u>intrinsic</u> <u>growth</u> <u>rate</u> of the population, and where K is a parameter known as the environmental carrying capacity or saturation level of the population.

The basic idea reflected in the logistic model formulation is quite simple. The rate of biomass accumulation at first increases with increasing biomass and then eventually decreases. This might reflect increasing opportunity for reproduction and/or growth as biomass increases from low levels to intermediate levels, and decreasing opportunities as biomass increases from intermediate to high levels due (for example) to competition for limited resources such as space, food, and water. These limiting resources define the capacity of the environment to sustain the population in question.

The dynamics of a population that obeys Equation (1) are easily analysed. In Figure 1, a phase diagram corresponding to Equation (1) is presented. As can be seen, there is one stable equilibrium population size, K, corresponding to the saturation population level. The population, if undisturbed, tends to this size asymptotically.

The solution to Equation (1) is the well-known logistic equation, and is given by

$$(2) \qquad S(t) = \frac{K}{1 + ce^{-rt}}$$

where

$$c = \frac{K - S(0)}{S(0)} ,$$

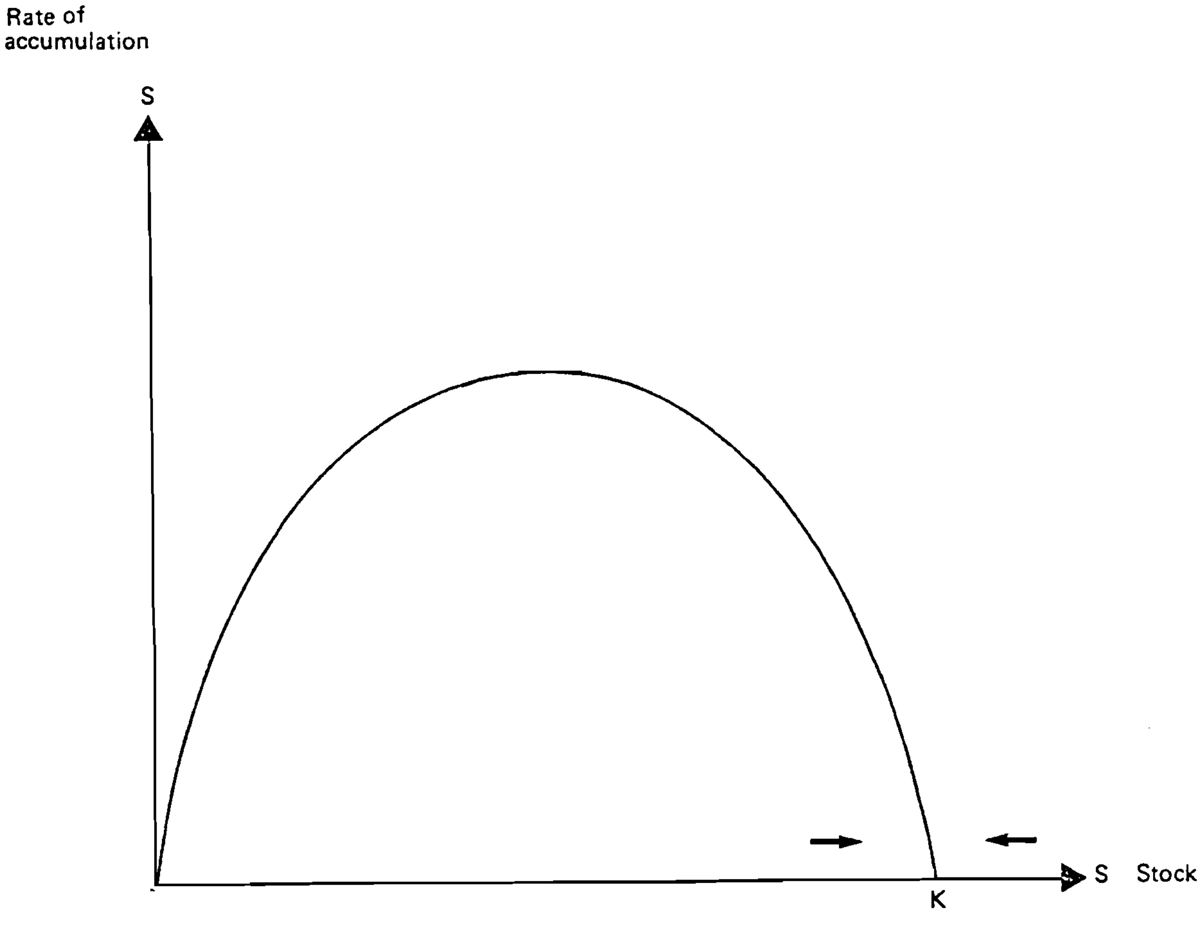

Figure 1. Logistic model of biomass accumulation

S(0) being the initial stock.

Equations (1) and (2) are formulated for the case in which time is continuously variable. It is useful, for empirical purposes, to recast Equation (2) as a difference equation. By suitable rearrangement, it can be shown that, in difference equation form,

$$(3) \qquad S(t+1) = \frac{aS(t)}{1 + (a-1)\dfrac{S(t)}{K}}$$

where $a = e^r$.

Equations (1) through (3) describe the natural dynamics of a population in the absence of any changes in external conditions, manipulation, or exploitation by other populations. Under these conditions, as noted above, we would expect to observe the population in question approach a steady size of K.

Now let us consider the possiblility of harvest of this population. To do this, we shall use Equation (3), and assume that harvest takes place instantaneously at the conclusion of each period. Letting h(t) be the harvest, the difference equation describing the evolution of population size becomes

$$(4) \qquad S(t+1) = \frac{aS(t)}{1 + (a-1)\dfrac{S(t)}{K}} - h(t)$$

Equation (4) may be used to derive the maximum sustainable annual harvest. To do this, note that for a harvest to be sustainable, it must result in neither an increase nor a decrease in the standing stock on a year-to-year basis. That is, sustainability requires that

$$(5) \quad (a-1)\, S(t) - (a-1)\frac{S(t)^2}{K} = h(t)$$

which may be derived by setting the left-hand-side of Equation (4) equal to S(t) and rearranging terms. Maximizing equation (5) with respect to S(t) gives the standing stock that results in maximum sustainable yield,

$$S(t) = 0.5\ K$$

which, substituted back into Equation (5), gives maximum sustainable yield

$$(6) \quad h_{max} = 0.25\ (a-1)\ K$$

This estimate in fact tends to overstate maximum sustainable yield under plausible harvest conditions, which do not--as is assumed in Equation (4)--harvest the resource in one impulse at the end of the period. An alternative estimate based on the assumption that harvest takes place continuously at a constant rate can be derived by finding the maximum of Equation (1) with respect to S, and substituting back into Equation (1). Estimates based on both procedures are reported here.

Equation (4) is the basic form of the equation we shall use in our subsequent empirical investigations. Although it is just about the simplest possible model, containing only two unknown parameters (a and K), available data permit only an approximate estimation of its parameters.

As was remarked above, it is possible to question the appropriateness of using the logistic model to analyze the population dynamics of guayule. In particular, it can be claimed with complete justification that the theoretical derivation of the model is based upon several assumptions that do not seem entirely appropriate in the case of guayule. These assumptions include the following:

(1)Biotic and abiotic factors are sufficiently constant in time and space as to not affect birth and death rates

(2)Density uniformly affects all population members

(3)Birth and death rates vary instantaneously and without lag in response to density changes

(4)The population has and maintains a stable age distribution

Guayule and its environment depart from these assumptions in several respects. For example, climate data show that the climate in guayule-growing areas is variable, and it is known that the standing stock of guayule is affected by weather conditions. This controverts Assumption (1). Ecological data also show that guayule is not distributed uniformly, but rather tends to occur in patches. These data call into question the appropriateness of Assumption (2). Harvesting may alter the age distribution of the population, thus calling Assumption (4) into question.

It is, in fact, possible to modify the basic logistic model to overcome many of these limitations. Smith (1980), for example, has shown how randomly varying environmental factors may be incorporated into the model, and how the concept of sustainability may be reinterpreted when randomness is present. Unfortunately, application of a modified model does not seem to be possible in the present context, due to lack of data.

In spite of its limitations, which certainly are not to be minimized, it is worth examination of the empirical implications of the model contained in Equation (4). In this regard, Pielou (1969, p 80) notes

> Extrapolation to populations for which the assumptions [i.e. the assumptions listed above] are, strictly speaking, unreasonable is often illuminating if cautiously done.

On this same point, May (1976, p 4) notes of the usefulness of applying simple models that do not explicitly represent all relevant interactions

> Even so, it is often useful to regard all these biological and physical interactions as passive parameters in an equation for the single population, summarizing them as some overall 'intrinsic growth rate', 'carrying capacity', or the like.

To proceed with full confidence that such a simple model is appropriate would require the examination of the model against experimental data. These data do not exist at the present time. Obtaining the required data is an important research priority if plans to produce guayule rubber commercially are to be pursued.

More will be said about this in the concluding section of the paper. In the absence of these data, however, it is still possible to check the implications of the model against other data taken from the period earlier this century when a guayule industry operated in Mexico. This we shall do.

3 DATA

The ideal set of data for estimation of the parameters of the model discussed in the preceding section would be a set of consistent inventories of standing stock of guayule, data on environmental conditions, data on the activities of possible predator species (e.g. goats are present in the Cedros area and graze on guayule), and data on shrub harvest. In contract the data actually available include a set of occasional shrub inventories, and a series of data on guayule rubber production (not shrub harvest). Each of these data sets is described below.

As far as could be ascertained, there have been nine inventories of the stock of guayule shrub in various parts of its region of occurrence. These inventories (and two additional related studies--McCallum (1942) and NPI (1980)) are summarized in Table 1.

Table 1
Inventories of Guayule Shrub

Inventory	Amount (1000 tons)	Density (tons/ha)	Remarks
Lloyd(1911)	500(original) 250(1911)	3.86	Field(Cedros)
Hargis(1942)	213	NE	Records(all regions)
McCallum(1942)	1/8 of 1910	NE	Observation(")
Cooperrider(1943)	260	2.00	Records+field(")
INIF(1974)*	304		Photo+field(C. Cienegas)
CONAZA(1976)*	462	1.93	Photo+field(C. Cienegas)
CONAZA(1977)	406	1.64	Photo+field(Saltillo)
CONAZA(1978)	1,527	1.79	Photo+field(Zacatecas)
NPI(1980)	NE	1.01	Field(Saltillo)
NPI(1981)	2,200	3.86	Landsat+field(Cedros)
CONAZA(1981)	600		Landsat+field(Cedros)

* Inventories covered different portions of Cuatro Cienegas

The first inventory is due to Lloyd (1911) in what, in many ways, must still today be regarded as the most comprehensive field investigation of guayule ever undertaken. Based on field investigations over a three-year period and on data and information collected from other sources (mainly the Intercontinental Rubber Company) during this same period, Lloyd estimated that the standing stock of guayule in the guayule region of Mexico was on the order of 250 thousand tons in 1910-11, and that this amount was approximately 1/2 of the standing stock that had existed in the area prior to the commencement of commercial guayule rubber production in the early 1900s. While Lloyd does state that his estimates of the stock pertain to the entire guayule area of Mexico, it is probable--given the location of his field investigations and the other sources he consulted--that his estimates pertain only to the guayule stands in a fairly large region around Cedros.

Lloyd's central purpose was other than estimating the standing stock of guayule, and, as a consequence, there are several ambiguities in his estimates. The most important of these is that it is not entirely clear whether his estimate refers to the exploitable stock of guayule (which--as a rough rule of thumb--could be taken to be accessible shrub over 25 cm high) or whether it is an estimate of the total amount of shrub, irrespective of size or location. Certain of his calculations suggest that the former is the correct interpretation (see for example the calculations presented in Lloyd (1911, pp 10-12)), and others (e.g. Lloyd (1911, pp 34-35)) suggest that the latter interpretation is correct.

Three more estimates were made during the mid years of World War II by U.S. Government employees dispatched (as a part of the U.S.'s Emergency Rubber Project) to Mexico to determine the quantity of rubber that could be obtained by harvesting the then-standing stock of guayule. O.D. Hargis (1942) estimated that the standing stock of exploitable guayule shrub (stem diameter approximately 2 cm) was about 213 thousand metric tons. He noted that this estimate did not include some shrub on government-owned land.

Because Hargis's estimates were based mainly on the records of the two rubber companies then producing guayule rubber in Mexico, the U.S. Department of Agriculture dispatched a team to make independent estimates based on field investigations. Cooperrider and Culley (1943) estimated a total stock of "merchantable shrub" in Mexico in 1942 of approximately 259 thousand metric tons. Of this total, they considered 222 thousand tons to be in areas in which accessibility was fair to good, and about 37 thousand tons to be scattered in stands in which accessibility was poor. These estimates were further broken down by geographic region.

W.B. McCallum, perhaps the leading botanical authority of the time on guayule, was also sent to assess the situation. McCallum (1942, p 24) reported as follows.

> I first went to Mexico in 1910 remaining there essentially two years, much of my time being spent on the range getting familiar with guayule in its natural habits of growth. Since then I have visited Mexico every three or four years. There has been one continuous change very noticeable every time, and that is the constant decrease in the amount of shrub to be seen at each visit.

McCallum (1942, p 23) further observed of his visit during the summer of 1942.

> I spent two months in Mexico last summer and went over many areas that I had known well in the past. The most noticeable condition to me was the continued decrease in the general volume of shrub now existing on the ranges. In many places where it once was abundant it is now virtually gone. And while in places there are still good stands, it is necessary to go farther and farther into the hills to get it. On the whole, there is probably now not more than one-eigth of the total tonnage of guayule shrub that there was in 1910.

There were, insofar as could be ascertained, no more estimates of the standing stock of guayule for over 30 years. Then, in 1974, as a result of revived interest in Mexico concerning the possibility of producing guayule rubber based upon wildstand harvest, the Instituto Nacional de Investigaciones Forestal (INIF) surveyed a portion of the area surrounding Cuatro Cienegas, and reported (on the basis of aerial photographs and field investigations) an estimated inventory of harvestable shrub (shrub over 25 cm in height) of 303 thousand tons. This inventory was later complemented in 1976 by the Comision Nacional de las Zonas Aridas (CONAZA), which surveyed the remaining area around Cuatro Cienegas, and reported an estimated 462 thousand tons of shrub in the balance of the Cuatro Cienegas area.

In 1977, CONAZA (1977) reported results of a survey of shrub in the region of Saltillo. According to this survey (also based on aerial photographs and field investigations), the Saltillo region contained approximately 406 thousand tons of harvestable shrub.

CONAZA completed its initial surveys of the guayule region in 1978, when it reported its results for the Zacatecas region. In this region, according to CONAZA (1978), there are approximately 1,527 thousand tons of harvestable shrub.

In 1980-1981, CONAZA resurveyed the portions of the Zacatecas and Saltillo regions surrounding the town of Cedros. Latest estimates, which are not yet published, suggest less shrub than had been estimated for corresponding areas in the previous CONAZA estimates. In a 130 km radius of Cedros, CONAZA now reports approximately 600 thousand tons of harvestable shrub.

Another estimate, based mainly on Landsat data and a modest amount of field work, has recently been made by Native Plants Inc. for the area within a 150 km radius of Cedros. According to NPI (1981), 2,200 thousand tons of harvestable shrub are available in this area. NPI (1981) notes, however, that this figure is biased upward (by an unknown amount) for two reasons. First, Landsat data were interpreted in a manner that biases estimates of the areal extent of guayule upward. Thus, some of the land area reported by NPI to contain guayule may in fact have none or have less than estimated. Second, in the field investigations, particularly good stands of guayule were selected for study. This undoubtedly accounts for the somewhat higher density figure reported in NPI (1981).

The second kind of data that are available for estimating the parameters of the model discussed in the preceding section are data on annual production of rubber from guayule. These data, can be used to estimate approximate quantities of shrub harvested. Ignoring inventories of shrub (which by all accounts were negligible due to the poor storage qualities of shrub), the shrub harvest in any year should be approximately proportional to rubber production in that year. Several observers have suggested that, on the average, the field weight of shrub harvest, over most of the period the industry operated in Mexico, was on the order of ten times the quantity of rubber produced. During the last few years of industry operations (i.e. 1943-1945), a factor of about 7.5 might, according to these same observers, be more appropriate. On this point, Hargis (1942) wrote:

> In the earlier years the percentage of extraction was very low and it is only in the last few years that average extraction of 14% to 16% has been obtained. It might be fairly assumed that over the entire period

> an average extraction of 10% was obtained, in which case it would have required around 900000 long tons (field weight) of shrub to produce this amount [i.e. the amount of rubber that had been produced up to 1942] of rubber.

Table 2 reports total Mexican annual production of guayule rubber. As can be seen, production fluctuated widely, largely reflecting demand conditions in international rubber markets. The high levels of production in the years circa 1910 and 1927 coincide with periods of relatively high international market prices for natural rubber. The high production levels of the 1940s reflect high wartime demand levels (prices were subject to wartime price controls).

Table 2
Mexican Production of Guayule Rubber

Year	Production(tons)	Year	Production(tons)
1905	375	1926	4,765
1906	1,819	1927	5,988
1907	4,305	1928	3,105
1908	5,432	1929	1,551
1909	8,438	1930	1,132
1910	10,738	1931	0
1911	8,032	1932	0
1912	6,935	1933	0
1913	2,205	1934	446
1914	298	1935	595
1915	1,552	1936	1,478
1916	317	1937	3,652
1917	1,150	1938	2,689
1918	2,015	1939	3,204
1919	1,214	1940	5,173
1920	1,100	1941	5,949
1921	32	1942	8,082
1922	308	1943	8,645
1923	1,371	1944	9,932
1924	1,538	1945	5,699
1925	4,157		

4 PARAMETER ESTIMATES

The basic strategy pursued here to estimate the parameters of Equation (4) is to select alternative estimates of standing stock at two different times and a corresponding value of K, and to find a value (if any) of the parameter "a" that -- given the intervening estimated harvest history -- yields these estimates of standing stock. With regard to the estimates of standing stock at different time priods, we have basically four different periods to choose from: (i) pre-exploitation (as described by Lloyd); (ii) estimates of standing stock circa 1910 (as reported by Lloyd); (iii) estimates made during 1942 (as reported by Hargis, Cooperrider and Culley, and commented on by McCallum); and (iv) estimates for circa 1975 (made by INIF, CONAZA, and NPI).

As should be clear from the discussion in the preceding section, the inventories available present a wide range of numbers from which to choose. Pending completion of current efforts to reconcile some of the discrepancies in current inventories, there is no fully satisfactory way to decide exactly which shrub stock estimates to use and how to use them. The most that can be done is to explore some alternatives and to endeavor to check their implications against other information.

One seemingly promising possibility for identifying shrub stocks at different points of time is offered by McCallum's estimate of the depletion of the total stock between 1910 and 1942, the Hargis and Cooperrider and Culley estimates of standing stock in 1942, and the implied total stock obtained by adding the INIF (1974), CONAZA(1976), CONAZA(1977), and CONAZA(1978) estimates. When the INIF and CONAZA estimates are added, we obtain an estimate of total standing stock circa 1975 of approximately 2,700 thousand tons in the entire guayule region of Mexico. If we multiply the Hargis or Cooperrider and Culley estimates of standing stock in 1942-43 by McCallum's depletion factor of approximately eight, we obtain an implied estimate of standing stock in 1910 of approximately 1,600 thousand to 2,080 thousand tons.

The estimates obtained by summing the INIF and CONAZA inventories and by multiplying the figures given by Hargis or Cooperrider and Culley are roughly consistent. The latter figure (i.e., a range of between 1,600 and 2,080 thousand tons) reflects an estimate of harvestable biomass after five years (i.e., from 1905 to 1910) of commercial exploitation. The former figure (i.e., of 2,700 thousand tons) reflects substantial recovery of the population after a period of 30 years (i.e., from 1945 to 1975) during which almost no harvesting was done.

The difficulty with this interpretation of the data is that, even if one assumes that guayule exhibited no natural growth, the production data reported in Table 2--multiplied by a factor of 10 to convert them into estimates of shrub harvest--could not conceivable reduce shrub stocks to the levels reported by Hargis or by Cooperrider and Culley. While the possibility that some other factors also reduced the supply of shrub over the period in question (e.g. grazing by goats and pests, unfavorable weather, fire) cannot be dismissed entirely, there is no evidence reported that these factors were significant compared to the effect of harvest. Another possibility is that far more shrub was harvested than is implied by the assumption that shrub field weight is 10 times the weight of rubber produced. A factor of 20, which is an appropriate factor today to produce high quality deresinated guayule rubber, would approximately reconcile an undisturbed population size estimate of approximately 2,000 thousand tons, the production history given in Table 2, and the 1942-43 estimates of standing stock. The difficulty with this line of argument, however, is that there is no basis for it in the literature, and that the factor of 10 seems approximately correct given probable resin, water, and other impurity content of the guayule rubber produced. These considerations, taken in conjunction with the fact that CONAZA recently has concluded that the estimates reported in INIF (1974), CONAZA (1976), CONAZA (1977), and CONAZA (1978) are biased upward, have lead us to abandon estimates based on the line of reasoning described above.

A somewhat more promising line of attack is to focus on estimates for the Cedros region. Although the full report remains to be published, it appears that the 1980-81 CONAZA estimate of harvestable shrub within a 130 kilometer radius of Cedros (approximately 600 thousand tons) will prove to be reasonably reliable. We might thus use this estimate as an estimate of shrub stock in the Cedros region after a substantial period during which almost no harvesting was conducted.

Of the 1942-43 estimates, only Cooperrider and Culley provided maps and reported their estimates by region. From these maps and the regional estimtes they present, it appears that the total quantity of shrub in a region corresponding roughly to that covered by CONAZA's 1980-81 estimate of the shrub in the area surrounding Cedros was about 230 thousand tons. This estimate could thus provide an estimate of the shrub population at another point of time.

As noted earlier, it also appears that Lloyd's investigations focused on the area around Cedros. Unfortunately, he does not provide maps, so it is not possible to be sure of the extent of the area he considered. Assuming that Lloyd covered roughly the same area as was covered by Cooperrider and Culley (1943) and by CONAZA (1981), we obtain two more estimates of shrub stock at two more times: approximately 500 thousand tons before exploitation (say 1905), and 250 thousand tons in 1910-11.

The difficulty with focusing on the Cedros region exclusively is that the production figures reported in Table 2, and hence the shrub harvest estimates calculated from them, pertain to total Mexican production, and not just production in the Cedros region. This may not be quite as serious as it at first seems. An investigation of the history of guayule rubber production in Mexico by Velazquez et al (1978) suggests that harvest was heavily concentrated in the region covered by the above estimates. It is probably valid to assume that virtually all of the production reported in Table 2 was based on shrub harvested in the Cedros region. We shall make this assumption.

Table 3 presents estimates of the parameter "a" and maximum sustained yield conditional on assumptions about initial and terminal standing stock and the carrying capacity parameter, K. In the uppermost block

Table 3
Estimates of Parameters of Equation (4)
(guayule in thousands of metric tons)

S(0)	S(T)	K	S(t)	a	h_{max}
500 (1905)	600 (1975)	606	249 (1911) 266 (1942)	1.2124	29 (32)
230 (1942)	600 (1975)	606	-----	1.2184	30 (33)

of the table, estimates are presented assuming an initial standing stock of 500 thousand tons, a terminal stock of 600 thousand tons, a saturation level of 606000 tons, and that shrub harvest was ten times the production levels reported in Table 2. Figures in parentheses are the dates corresponding to the values reported above. The column of the table headed by "a" reports the estimate of "a" in Equation (4) that, given the estimated harvest and initial condition, results in an estimated population consistent with the assumed terminal value. As can be seen, the estimated value of "a" under the conditions assumed is 1.2124.

The column headed S(t) reports estimated population at selected intermediate dates (shown in parentheses below the corresponding figure) assuming the value of "a" reported in the column next to it. Thus, given the initial condition, harvest history, and a=1.2124, Equation (4) implies a 1911 population of 249 thousand tons of guayule, and a 1942 population of 266 thousand tons of guayule. Both of these figures correspond reasonably well with estimates reviewed in the preceding section.

The rightmost column reports estimated maximum sustained yield. Two estimates--one corresponding to the maximum of Equation (1) and the other (shown in parentheses) corresponding to the maximum of Equation (5)-- are presented. As can be seen, under the conditions assumed in the computations reported at the top of Table 3, estimated maximum sustained yield are 29,179 and 32,179 tons per year, respectively.

The lower portion of the table reports estimates based on Cooperrider and Culley's estimate of shrub in the Cedros region in 1942-43 and the most recent CONAZA estimate. Using these figures, and assuming that rubber weight was 15 percent of shrub weight in 1942 and beyond, an estimate of "a" of 1.2184 is obtained, along with corresponding estimates of maximum sustained yield of 29,922 and 33,038 tons per year.

The data and estimates presented in Table 3 thus lead uniformly to the conclusion that the maximum sustained yield of harvest of wildstands in approximately a 130 kilometer radius of Cedros is roughly 30 thousand tons per year. It is relatively easy to fashion a great many additional estimates based on alternative estimates of environmental carrying capacity, and alternative assumptions about intitial and terminal shrub stock values and ratios of shrub weight to rubber weight. Several such additional estimates have been made. Many of these were devoted to testing the sensitivity of the estimates of maximum sustained yield to the value selected for K. In general, changes in K produced produced roughly offsetting changes in the corresponding estimate of "a", with the result that estimated maximum sustained yield changed very little. Ranges of values for which one can find some support in the literature do not materially change the above conclusion concerning the probable level of maximum sustained yield in the vicinity of Cedros.

Moreover, as has been noted above, there is additional evidence to substantiate this conclusion. First, recall repeated observations that industry operations during the period 1905 - 1945 had resulted in depletion of the stock of shrub. Lloyd (1911) found that the harvest levels of the first six years of operation of the industry had depleted the shrub stock to about one-half of its pre-exploitation level. McCallum (1942) reported continual depletion of the standing stock (see above). Over the period up to and including 1942, the average annual production of rubber was 2,915 tons per year. If years in which no production took place are excluded (i.e. 1931-33), the average is 3,165 tons per year. As can be seen from the table, there were several runs of years during which production levels were well above this average level. Using a ratio of shrub weight to rubber weight of 0.10 (see above), this corresponds to an estimated annual harvest of approximately 30 thousand tons of shrub, field weight. This estimate, taken in conjunction with observations of the continual depletion of the standing stock, suggests that our approximate estimate of maximum sustained yield may, if it is biased at all, be biased upward.

Second, Recio (1979) reports that harvest-worker productivity fell from approximately 500 kilograms per day in the late 1930s to approximately 100 kilograms per day in the mid-1940s. It is also reported that the price per ton of shrub a Torreon jumped from 10 pesos to 40 pesos in the late 1930's, and to 80 pesos in the mid-1940s. Recio attributes these changes to the increasing scarcity of shrub.

5 IMPLICATIONS FOR CURRENT PLANS

The implications of the above results for current plans to construct and operate a plant producing 5 thousand tons of guayule rubber per year are clear: in all likelihood, shrub productivity in the region of the plant is inadequate to sustain this level of rubber production. Every ton of guayule rubber produced today, using modern processing techniques and shrub of the average rubber content of harvestable shrub found in the Cedros region (ranging from 10 to 11 percent pure rubber on a defoliated dry-weight basis) requires approximately 20 tons of shrub field weight. That is, the ratio of weight of rubber produced to field weight of shrub harvested is approximately 0.05. The reason for the decline in rubber weight to field weight ratio from that which obtained between 1905 and 1945 (recall from above that this ratio was appoximately 0.10 during the first half of this century) is that the rubber produced today contains almost no moisture (which used to account for about 25 percent of the weight of the rubber product during the period reported in Table 2) and almost no resin (which also used to account for about 25 percent of the weight of the product).

Using a product weight to field weight ratio of 0.05, an initial stock of 600 thousand tons, and a value of "a" of 1.215, it is estimated that the wildstands of harvestable shrub would be completely depleted within eight years. Of course it is probable that exploitation would run into serious difficulties well before the point of complete exhaustion of the stock. Harvestable shrub would become more difficult to locate and more expensive (due to decreased density) to harvest and transport. The data cited above on the decline in harvest productivity and increase in shrub costs during the 1940s attest to the importance of these factors.

The depletion rates implied by annual guayule rubber production at a rate of 5 thousand tons do not leave much room for maneuver. Even if it were feasible to begin reforestation and/or dryland cultivation of guayule simultaneously with the commencement of production from the wildstands, it probably would take from five to seven years before the first managed stands could be harvested.

Scaling-back production from wildstands could buy quite a bit of time. Table 4 below shows estimated times to exhaustion at a number of lower production levels. Scaling-back to 4 thousand tons per year of rubber

Table 4
Estimated Years to Exhaustion of Wildstands at Alternative Rubber Production Levels

Annual Rubber Production (tons)	Estimated Years to Exhaustion
4000	11
3500	13
3000	16
2500	20+

extends the estimated life of the wildstands to 11 years. Scaling-back to one-half of the currently planned capacity, i.e., to 2,500 tons, stretches out the period of exhaustion to more than 20 years. Based on our estimate of maximum sustainable yield, a processing plant of approximately 1,500 tons per year capacity could operate at this level indefinitely (i.e. 0.05 x 30,000 = 1,500).

6 CONCLUSIONS

Three conclusions may be drawn from the analysis presented in the preceding sections. First, it is probable (but by no means absolutely certain) that the maximum sustainable yield from wildstand harvest in the Cedros region is no more than 30 thousand tons per year. This conclusion is supported both by estimates of the parameters of a simple (admittedly perhaps overly so) model of biomass accumulation, by direct observation of the effects of harvesting at approximately this level (i.e., 30 thousand tons per year) over the period from 1905 to 1945, and by indirect evidence of shrub scarcity in the form of observations on harvest productivity and the delivered cost of shrub at the factory gate.

Second, much more needs to be understood about the dynamics of the guayule population, and the effects on that population of alternative harvest methods (e.g., harvest by pulling the entire plant versus harvest by cutting the plant), possible management techniques (e.g., application of biostimulants to increase rubber accumulation, selective reduction of competition), and environmental factors (e.g., meteorological conditions, predation). Given plans to reactivate the guayule rubber industry in Mexico, initially based on the harvest of wildstands, it is clear that these topics deserve the highest possible research priority.

Four lines of attack should be pursued to make the most rapid possible progress in understanding guayule population dynamics. First, a much more systematic effort to reconcile existing inventories of guayule should be undertaken. The bases of each need to be identified and carefully compared, and the raw data need to be examined. In general, all of the field investigations seem to have arrived at good characterizations of the plots studied. The main discrepancies, I think, will be found in the experimental design and the extrapolations from the field experiments. Resolution of these discrepancies undoubtedly will require some additional field work. Second, a series of carefully designed and monitored harvesting experiments are needed. These should determine the effect of harvest on the regeneration and age-size structure of stands. Third, since commercial harvest operation apparently will begin before any harvesting experiments could be considered to be complete, an effort should be made to identify control plots in the commercial harvest area and to monitor their regeneration. Fourth, ecological data collected in the various inventories should be analyzed to determine what can be inferred from them about population dynamics.

Finally, production of any substantial quantity of guayule rubber annually will require cultivation of guayule. While a substantial body of knowledge concerning the growth and rubber content of the guayule shrub under cultivation has been accumulated, it is not at present known whether or not large scale cultivation is feasible. Examination of this question is also vitally important, particularly if production rates that could result in rapid depletion of wildstands are contemplated.

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