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Cutting height effects on guayule latex, rubber, and resin yields

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ABSTRACT

Guayule (*Parthenium argentatum* Gray) is a perennial shrub native to the Chihuahuan Desert. While guayule traditionally has been cultivated for rubber, more recently it is being cultivated for its hypoallergenic latex. Other uses including termite resistant wood products and as an energy source have also been identified. Major advances have been made since 1970 in the development of improved guayule germplasm. However, the effects of harvesting practices such as cutting height and frequency on latex concentration and yield of newly developed germplasm have not been reported. These results are needed in order to develop production schemes for successful commercialization of guayule. The objectives of this study were to determine the yield and concentration of latex, rubber, and resin of five guayule lines harvested at two cutting heights over 3 years and five harvesting schedules. Harvesting at 100% of plant height gave higher yields than harvesting at 50% of plant height independent of the harvest schedule. Harvesting at 100% after 4 years of growth gave the highest yields, but more research is needed to determine if harvesting on a 2-year schedule may be better for harvesting equipment and extraction equipment. AZ-2 and AZ101 were the largest plants, while N9-3 and 11591 were smaller with AZ-1 intermediate. As indicated in previous studies, the environment plays a large role in determining biomass, latex, rubber, and resin yields in guayule. In the future, optimum harvesting schemes at 100% of plant height may need to be developed for each line and environment.

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1. Introduction

Guayule's use as a natural rubber source dates back before 1500 A.D. when Native Americans used its latex to make balls for games. Guayule has been evaluated in the U.S. as a potential commercial rubber crop during at least three periods prior to the current efforts in response to various international crises (Foster and Coffelt, 2005; Ray et al., 2005). The latest period of commercialization began in the 1980s and overlaps with the end of the preceding period. This current period was initiated when the AIDS epidemic began. In response to increased demand for latex medical products and as a result of short cuts in manufacturing processes to meet this demand, many people developed latex allergies ranging from contact dermatitis to anaphylactic shock (Ownby et al., 1994). Research showed that guayule latex did not contain the allergy causing proteins present in *Hevea* latex (Siler et al., 1996). Thus, an important difference between the current period and previous commercialization attempts of guayule is that the rubber is in the latex form rather than solid rubber. This is important, because the latex of guayule does not compete directly with less expensive *Hevea* rubber for such uses as tires, but rather with more expensive synthetic latex and *Hevea* latex in the medical devices market. Guayule latex as a natural latex has many advantages over the more expensive synthetic sources and can be made into high value medical products such as catheters, tubing, condoms, surgical balloons, and gloves.

Research has also been expanded to evaluate other potential products from guayule (Nakayama et al., 2003a,b). After latex extraction, over 90% of the plant biomass remains and must provide an economic return for guayule to be successful commercially. One area of research has focused on the use of the residual biomass to produce composite wood products. These products have been shown to be termite and wood rot resistant due to the resin in guayule (Nakayama et al., 2003a). Guayule resin has also been used to impregnate termite susceptible wood products to provide resistance to termites. These findings give guayule another use that may prove to be as valuable as the hypoallergenic latex.

Another area that has recently received renewed attention is the use of guayule as an energy crop. Preliminary studies by Nakayama et al. (2003b) indicate that the biomass of the whole plant has higher energy values (21.77 MJ kg^{-1}) than other plant biomass sources such as corn (*Zea mays* L.) stalks, wheat (*Triticum aestivum* L.) straw, kenaf (*Hibiscus cannabinus* L.), and switchgrass (*Panicum virgatum* L.) (18.61 MJ kg^{-1}). Guayule resin (37.90 MJ kg^{-1}) has energy values comparable to the oil extracted from most oilseed

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Table 1
Treatment numbers, cutting height (50% vs. 100%), year(s) harvested, and growth type (original vs. regrowth) for five guayule lines grown at Maricopa, AZ, USA.

Treatment number	Cutting height	Year(s)	Growth type
1	50%	2003, 2004, 2005	Original (2003), regrowth (2004, 2005)
2	50%	2003, 2005	Original (2003), regrowth (2005)
3	100%	2003, 2004, 2005	Original (2003), regrowth (2004, 2005)
4	100%	2003, 2005	Original (2003), regrowth (2005)
5	50%	2004	Original
6	100%	2004	Original
7	50%	2005	Original
8	100%	2005	Original

crops and can be used as fuel. The entire plant biomass with both the rubber (latex) and resin removed is still equal to or higher (20.49 MJ kg^{-1}) than other plant biomass sources in energy value (Nakayama et al., 2003b).

Ray et al. (2005) recently reviewed previous work on breeding guayule, and Foster and Coffelt (2005) on agronomic research on guayule. Major advances have been made since 1970 in the development of improved guayule germplasm. Previously, the time to harvest was generally considered to be from 3 to 5 years, but with the latest germplasm releases the harvest period has been reduced to 2–3 years (Ray et al., 1999). In addition to faster growth, new lines also have higher rubber and/or resin yields than the older lines. Experimental biomass yields of 22 t ha^{-1} for these newer lines have been achieved within 2 years.

The effects of various agronomic practices such as increased plant population, transplanting date, and post-harvest storage on the latex, rubber, and resin contents and yields of guayule have been reported for the newer germplasm lines (Dierig et al., 2001; Coffelt et al., 2005, 2009a,b; Dissanayake et al., 2007). These studies were all conducted with plants harvested by the recommended practice of harvesting the whole above ground portion of the plant (Foster and Coffelt, 2005; Coffelt and Nakayama, 2007). Preliminary results have indicated that the small to medium size branches contain most of the latex. Thus if only those branches were harvested, yields of latex might be increased. Another potential benefit may be faster regrowth following harvest, allowing more frequent harvests than every 2 years. The objectives of this study were to determine the yield and concentration of latex, rubber, and resin of five guayule lines harvested at two cutting heights and four harvesting schedules over 3 years.

2. Materials and methods

Five guayule lines were used in this study (AZ-1, AZ-2, AZ-101, N9-3, and 11591). The newly released germplasm lines AZ-1 and AZ-2 were selected for higher rubber and resin concentration and biomass production (Ray et al., 1999). AZ-101 is an older breeding line with higher biomass. N9-3 is an unreleased breeding line with higher rubber and resin contents, but lower biomass than AZ-1 and AZ-2. Preliminary tests have also indicated that N9-3 may be more tolerant to colder growing conditions than the other lines (Foster et al., 2008). 11591 is an older USDA line used as the check. Seedlings were started in the greenhouse and transplanted in the field at about 3 months of age at The University of Arizona Maricopa Agricultural Center, Maricopa, AZ, USA on 12 April 2001. The initial plant population was 27,000 plants ha^{-1}. All treatments were well watered with no obvious nutrient deficiencies or pest problems throughout the experiment. The experimental design was a randomized complete block factorial design with four replications. Guayule lines and eight harvest height and frequency treatments (Table 1) were considered fixed effects in the analyses. Rows were 1.0 m apart and each split plot was 4.3 m long for a harvested area of 4.3 m^2.

Treatment 4 (Table 1) of the treatments is the currently recommended method of harvesting 100% of the above ground plant material when plants reach 2 years of age then harvesting the regrowth after another 2 years (Foster and Coffelt, 2005). Treatment 2 was a modification of this with only the upper 50% of the plant height harvested after 2 years of growth and again after 2 years of regrowth. Treatments 1 (50%) and 3 (100%) involved harvesting every year after the plants reached 2 years of age at the indicated plant heights. Treatments 5 (50%) and 6 (100%) were harvested only once after 3 years of growth at the indicated heights. Treatments 7 (50%) and 8 (100%) were also only harvested once after 4 years of growth at the indicated heights. Treatments 4, 6, and 8 give a measure of the total plant growth that occurred after 2, 3, and 4 years of growth respectively.

Harvested plants were analyzed for dry biomass weight, latex concentration and yield, rubber concentration and yield, and resin concentration and yield. All plots were harvested and chipped using the method described by Coffelt and Nakayama (2007), except treatments harvested at 50% of plant height. These treatments were harvested with a hedge trimmer at 50% of the average total plant height for the plot and the cut material chipped as with the 100% treatments. All plants within the 100% cutting height treatments were cut within 5 cm of the soil surface and all above ground plant material chipped. All plant material was chipped into antioxidant solution (0.2% sodium sulfite in distilled water at a pH of about 11) to preserve the latex (Coffelt and Nakayama, 2007). Two subsamples were taken from the freshly chipped material and put on ice. One sub-sample was processed for latex concentration and one for rubber and resin concentration. Latex concentration was determined by the water extraction method described by Cornish et al. (1999). Rubber and resin concentrations were determined by a modification of the organic solvent based gravimetric method of Black et al. (1983) as described by Veatch-Blohm et al. (2006). Latex, rubber, and resin yields are derived from the latex, rubber, or resin concentration multiplied by the total biomass. All values reported are based on plant dry weights from the harvested plots. Data were analyzed by analyses of variance and means separated by LSD at the $P = 0.05$ level.

3. Results and discussion

The results from harvest of 2-year-old plants in 2003 (Table 2) showed that both treatments cut at 100% of plant height (Treatments 3 and 4) were significantly higher in biomass, latex, rubber, and resin yields than those cut at 50% of plant height (Treatments 1 and 2). AZ-1, AZ-2, and AZ-101 were higher in biomass, latex, rubber, and resin yields than N9-3 and11591. Even though AZ-1 was lower in biomass its latex concentration was higher than AZ-2 and AZ-101 so that the total latex yield was not significantly different among the three lines.

Similar results were found after 3 years of growth in the 2004 harvests (Table 3). Plants harvested at 100% of plant height (Treatment 6) were higher in biomass, latex, rubber, and resin yields than those harvested at 50% of plant height (Treatment 5). The

Table 2
Biomass, latex, rubber, and resin yields for five guayule lines and four cutting height – frequency treatments harvested in 2003 after 2 years of plant growth.

Main factor	Biomass, g/m^2	Latex, g/m^2	Rubber, g/m^2	Resin, g/m^2
Treatment[a]				
1 (50%, original, 2 years)	941 b[b]	7.19 b	44.61 c	84.19 b
2 (50%, original, 2 years)	851 b	6.99 b	35.18 c	79.45 b
3 (100%, original, 2 years)	2173 a	18.69 a	105.52 a	208.86 a
4 (100%, original, 2 years)	2154 a	14.44 a	86.26 b	201.77 a
Line				
AZ-1	1717 b	18.08 a	74.89 b	163.39 b
AZ-2	2308 a	14.18 a	96.79 a	223.20 a
AZ-101	2179 a	13.81 a	87.70 ab	209.07 a
N9-3	589 c	6.04 b	32.39 c	60.53 c
11591	855 c	7.03 b	47.70 c	61.64 c

[a] Treatment codes are in Table 1.
[b] Letters within a column and main factor followed by the same letter are not significantly different according to LSD at the $P = 0.05$ level.

treatments harvested at both 50% (Treatment 1) and 100% (Treatment 3) of plant height after 1 year of regrowth were lower in biomass, latex, rubber, and resin yields than Treatments 5 and 6. These results are not unexpected since Treatments 5 and 6 are the result of 3 years of growth, while Treatments 1 and 3 are the result of only 1 year of regrowth. One would expect plants that have been growing for 2 years longer to have more biomass, latex, rubber, and resin than those growing for only 1 year. In addition, the amount of regrowth for Treatments 1 and 3 was not significantly different indicating that harvesting at 50% of plant height did not result in more regrowth than at 100% after 1 year of regrowth. Results for lines across all treatments were the same as the first harvest with AZ-1, AZ-2, and AZ-101 highest in biomass, rubber, and resin yields, and N9-3 and 11591 lowest in biomass, latex, rubber, and resin yields. Similar results to those in 2003 were also observed for AZ-1 having higher latex concentrations than the other lines, which allowed it to have similar latex yields to AZ-1 and AZ-101 even though AZ-1 had lower biomass yields.

Results after 4 years of growth followed the same pattern as the two previous years (Table 4). The plants harvested at 100% of plant height (Treatment 8) were higher in biomass, latex, rubber, and resin yields than the other treatments. The lowest yields occurred for those plants harvested annually at 100% of plant height (Treatment 3) and those harvested annually at 50% of plant height (Treatment 1). The differences in treatments is not unexpected, since Treatments 7 and 8 represent 4 years of growth, Treatments 2 and 4 two years of regrowth, and Treatments 1 and 3 only 1 year of regrowth. One would expect plants that have been growing longer to be higher in biomass than those with only 1 or 2 years of growth. Results for the lines across all treatments were similar to those for

Table 3
Biomass, latex, rubber, and resin yields for five guayule lines and four cutting height – frequency treatments harvested in 2004.

Main factor	Biomass, g/m^2	Latex, g/m^2	Rubber, g/m^2	Resin, g/m^2
Treatment[a]				
1 (50%, regrowth, annual)	673 c[b]	8.60 c	30.65 c	53.20 c
3 (100%, regrowth, annual)	819 bc	8.92 c	35.96 c	69.77 c
5 (50%, original, 3 years)	1153 b	27.08 b	69.51 b	115.29 b
6 (100%, original, 3 years)	2970 a	60.86 a	179.07 a	283.21 a
Line				
AZ-1	1516 b	30.98 a	82.26 bc	144.56 b
AZ-2	2120 a	38.98 a	118.16 a	204.41 a
AZ-101	2062 a	33.31 a	102.04 ab	196.31 a
N9-3	421 d	10.22 b	29.13 d	40.39 c
11591	900 c	18.33 b	62.39 c	66.18 c

[a] Treatment codes are in Table 1. Treatments 1 and 3 after 1 year of regrowth and Treatments 5 and 6 after 3 years of growth.
[b] Letters within a column and main factor followed by the same letter are not significantly different according to LSD at the $P = 0.05$ level.

Table 4
Biomass, latex, rubber, and resin yields for five guayule lines and six cutting height – frequency treatments harvested in 2005.

Main factor	Biomass, g/m^2	Latex, g/m^2	Rubber, g/m^2	Resin, g/m^2
Treatment[a]				
1 (50%, regrowth, annual)	1033 cd[b]	8.93 cd	38.89 de	98.21 cd
2 (50%, regrowth, biennial)	1291 bc	18.64 bc	60.25 cd	136.37 bc
3 (100%, regrowth, annual)	634 d	4.67 d	21.11 e	56.63 d
4 (100%, regrowth, biennial)	1576 bc	20.17 b	66.44 c	147.07 bc
7 (50%, original, 4 years)	1793 b	26.07 b	93.91 b	188.35 b
8 (100%, original, 4 years)	4293 a	57.71 a	223.53 a	405.26 a
Line				
AZ-1	1852 b	27.37 a	89.95 b	187.95 b
AZ-2	2664 a	29.64 a	116.81 a	261.44 a
AZ-101	3099 a	35.24 a	129.55 a	300.56 a
N9-3	496 c	9.38 b	35.66 c	52.19 c
11591	738 c	11.88 b	48.13 c	57.79 c

[a] Treatment codes are in Table 1. Treatments 1 and 3 after 1 year of regrowth, Treatments 2 and 4 after 2 years of regrowth, and Treatments 7 and 8 after 4 years of growth.
[b] Letters within a column and main factor followed by the same letter are not significantly different according to LSD at the $P = 0.05$ level.

Table 5
Total biomass, latex, rubber, and resin yields for five guayule lines and four cutting height – frequency treatments harvested in 2003 and 2004.

Main factor	Biomass, g/m^2	Latex, g/m^2	Rubber, g/m^2	Resin, g/m^2
Treatment[a]				
1 (50%, regrowth, annual)	1614 b[b]	15.79 c	75.27 c	137.39 b
3 (100%, regrowth, annual)	2999 a	27.61 b	141.48 b	278.63 a
5 (50%, original, 3 years)	1153 c	27.08 b	69.51 c	115.29 b
6 (100%, original, 3 years)	2970 a	60.86 a	179.07 a	283.21 a
Line				
AZ-1	2435 b	41.88 a	125.66 b	232.72 b
AZ-2	3224 a	45.70 a	171.47 a	311.53 a
AZ-101	3177 a	40.90 a	150.01 ab	301.98 a
N9-3	736 d	13.52 b	46.35 d	72.77 c
11591	1349 c	22.18 b	88.09 c	99.16 c

[a] Treatment codes are in Table 1. Treatments 1 and 3 include values from initial harvest in 2003 plus values from 1 year of regrowth harvested in 2004, while Treatments 5 and 6 are from 3 years of growth.
[b] Letters within a column and main factor followed by the same letter are not significantly different according to LSD at the $P = 0.05$ level.

previous years. AZ-2 and AZ-101 were highest for biomass, rubber, and resin yields, and AZ-1, AZ-2, and AZ101 were highest for latex yield. N9-3 and 11591 were lowest in yield for all traits. The results for AZ-1 support the previous 2 years in that AZ-1 was higher enough in latex concentration than AZ-2 and AZ-101 to compensate for lower biomass yields so that the resulting latex yield of AZ-1 (biomass × latex concentration) was equal to AZ-2 and AZ-101.

While comparison of the annual yields is useful, we were more interested in looking at the total yields of treatments across all years of harvest (Tables 5 and 6). The total yields for Treatments 1 and 3 that were harvested in both 2003 and 2004 were compared to the yield for Treatments 5 and 6 that were harvested only in 2004 (Table 5). The total yields for the treatments harvested at 100% plant height (Treatments 3 and 6) were not significantly different for biomass and resin yields, but the latex and rubber yields were less for the multiple harvest (Treatment 3). The two treatments harvested at 50% of plant height (Treatments 1 and 5) were significantly less than either of the treatments harvest at100% of plant height (Treatments 3 and 6). Differences among lines did not change whether looking at total yields (Table 5) or yields for 1 year (Table 3) when averaged across treatments. AZ-2 and AZ-101 were the highest for biomass, rubber, and resin yields, while N9-3 and 11591 were the lowest. AZ-1 was intermediate for these traits, but equal to AZ-2 and AZ-101 for latex yield.

Biomass yields of plants harvested at 100% of plant height either annually (Treatment 3), biennially (Treatment 4), or once after 4 years (Treatment 8) were not significantly different (Table 6). However, Treatment 8 was higher for latex, rubber, and resin yields than the other 100% treatments. Total biomass yields of plants harvested at 50% of plant height were lower than those harvested at 100% of plant height (Treatments 1, 2, and 7). Treatment 1 (annual harvest at 50%) was higher for biomass yield than Treatment 7, while no differences occurred for latex, rubber, or resin yields among the 50% plant height treatments. Differences in lines again did not change whether comparing results averaged over years (Table 6) or for an individual year (Table 4). AZ-2 and AZ-101 were highest for biomass, rubber, and resin yields, while AZ-1, AZ-2, and AZ-101 were the highest for latex yield. N9-3 and 11591 were consistently lower for yields of all traits.

Harvesting at 50% of plant height did not prove to be better than harvesting at 100% of plant height. We did notice some plants did not regrow well when cut at 100% for 3 years. The amount of regrowth biomass for Treatment 1 (50% harvested annually) and Treatment 3 (100% harvested annually) was similar after one harvest (Table 3), but lower for Treatment 3 after 2 years of cutting indicating that there may be some negative effects to harvesting at 100% for more than one or 2 years on plant biomass. However, this did not translate into lower total latex yields compared to the 50% treatments.

Differences in lines were as expected based on previous reports (Dierig et al., 2001; Coffelt et al., 2005, 2009a,b; Dissanayake et al., 2007) with AZ-2 and AZ-101 being larger than the other lines and N9-3 and 11591 being the smallest. There were few significant interactions among lines and treatments with most occurring in 2003. However, the interaction effects were smaller than the main effects and due mainly to N9-3. Total biomass yields and total resin yields were highest for all lines, except N9-3 when harvested at 100% after 4 years (Treatment 8). N9-3 gave higher biomass yields

Table 6
Total biomass, latex, rubber, and resin yields for five guayule lines and four cutting height – frequency treatments harvested in 2003, 2004, and 2005.

Main factor	Biomass, g/m^2	Latex, g/m^2	Rubber, g/m^2	Resin, g/m^2
Treatment[a]				
1 (50%, regrowth, annual)	2648 b[b]	24.71 b	114.16 c	235.60 c
2 (50%, regrowth, biennial)	2142 bc	25.63 b	95.43 c	215.81 c
3 (100%, regrowth, annual)	3633 a	32.28 b	162.59 b	335.26 b
4 (100%, regrowth, biennial)	3685 a	34.61 b	152.70 b	348.86 ab
7 (50%, original, 4 years)	1793 c	26.07 b	93.91 c	188.35 c
8 (100%, original, 4 years)	4293 a	57.71 a	223.53 a	405.26 a
Line				
AZ-1	3282 b	43.17 a	152.34 b	320.09 b
AZ-2	4536 a	43.05 a	195.44 a	437.67 a
AZ-101	4955 a	48.81 a	204.60 a	474.65 a
N9-3	937 c	14.64 b	62.19 c	100.48 c
11591	1451 c	17.85 b	87.36 c	108.02 c

[a] Treatment codes are in Table 1. Treatments 1 and 3 include values from initial harvest in 2003 plus values from 1 year of regrowth harvested in 2004 plus 1 year of regrowth harvested in 2005. Treatments 2 and 4 include values from initial harvest in 2003 plus 2 years of regrowth harvested in 2005. Treatments 7 and 8 are from the initial harvest of 4 years of growth.
[b] Letters within a column and main factor followed by the same letter are not significantly different according to LSD at the $P = 0.05$ level.

when harvested at 100% annually (Treatment 3), but this was not significantly higher than the other 100% treatments for N9-3 (Treatments 4 and 8). Resin yields for N9-3 were higher when harvested on a biennial schedule at 100% of plant height (Treatment 4). All lines, except AZ-101 had their highest total latex yields when harvested after 3 years of growth at 100% (Treatment 6). AZ-101 had its highest latex yield when harvested at 100% after 4 years of growth (Treatment 8). Rubber yields were highest for all lines when harvested after 4 years at 100% of plant height (Treatment 8), except for 11591 which was higher when harvested after 3 years at 100% (Treatment 6).

More research will need to be done to determine the most economic harvest scheme when comparing harvesting at 100% every 2 years (Treatment 4) vs. a single harvest at 100% after 4 years. Even though Treatment 8 was higher for yields of latex and rubber than Treatment 4 the ease of passing a harvester through the field and handling smaller branches through an extraction plant may be beneficial and offset the increase in yields of latex and rubber. Additional benefits such as more flexibility in crop rotations with biennial harvests may also make a 2-year harvest schedule more desirable.

4. Conclusion

Harvesting at 100% of plant height gave higher yields than harvesting at 50% of plant height independent of the harvest schedule. Harvesting at 100% after 4 years of growth gave the highest yields, but harvesting on a 2-year schedule may be better for harvesting equipment and extraction equipment. AZ-2 and AZ101 were the largest plants, while N9-3 and 11591 were smaller with AZ-1 intermediate. As indicated in previous studies (Dierig et al., 2001; Coffelt et al., 2005, 2009a,b; Dissanayake et al., 2007), the environment plays a large role in determining biomass, latex, rubber, and resin yields in guayule. In the future, optimum harvesting schemes at 100% of plant height may need to be developed for each line and environment.

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