Journal of Cleaner Production 273 (2020) 122811

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Integrated techno-economic and environmental analysis of guayule rubber production

Evan Sproul [a, *], Hailey M. Summers [a], Clark Seavert [b], Joram Robbs [c], Sita Khanal [c], VeeAnder Mealing [d], Amy E. Landis [d], Neng Fan [e], Ou Sun [e], Jason C. Quinn [a]

[a] Department of Mechanical Engineering, Colorado State University, Fort Collins, CO, 80523, USA
[b] Department of Applied Economics, Oregon State University, Corvallis, OR, 97331, USA
[c] Department of Agricultural Economics and Agricultural Business, New Mexico State University, Las Cruces, NM, 88003, USA
[d] Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO, 80401, USA
[e] Department of Systems and Industrial Engineering, University of Arizona, Tucson, AZ, 85721, USA

ARTICLE INFO

Article history:
Received 4 February 2020
Received in revised form
13 April 2020
Accepted 10 June 2020
Available online 13 July 2020

Handling Editor:Prof. Jiri Jaromir Klemeš

Keywords:
Industrial crops
Bioproducts
Life cycle assessment
Technoeconomic analysis
Sustainability
Drought

ABSTRACT

Persistent drought poses a significant risk to farmers in the southwest United States. Adopting drought tolerant crops that yield high value products will help mitigate this risk. One potential crop is guayule, which is known for its high natural rubber content. In this work, a process model was created to quantify all materials and energy required to cultivate, harvest, transport, and extract guayule rubber and co-products. This process model was used to enable the first concurrent techno-economic and environmental analysis of guayule. The techno-economic and environmental results include two scenarios: 1) a baseline scenario in which bagasse and resin are sold at predefined values and 2) an on-site heat and power scenario in which bagasse is combusted to generate heat and electricity. The result of the techno-economic analysis for the baseline scenario was a minimum rubber selling price of $3.08 per kg, with co-products of resin and bagasse being sold at $1.00 and $0.10 per kg, respectively. Baseline environmental results show that the largest impacts come from the use of fertilizers in agriculture and natural gas in the rubber extraction facility. The on-site heat and power analysis found an increased minimum rubber selling price of $4.07 per kg, but also a 61% decrease in global warming emissions. Discussion focuses on leveraging results to further the development of guayule by identifying high impact areas where future research may simultaneously reduce costs and environmental impacts.

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1. Introduction

A growing population and uncertain future climate conditions are increasing the likelihood of water shortages in the southwest United States(Global Change Resear, 1524). These shortages pose significant risk to regional agriculture, which requires a large amount of water for supplemental irrigation (Cooley, 2016). Shifting agriculture to include crops that require less water may help mitigate these risks. However, these crops must also generate adequate revenue to offset the costs of production and provide income to farmers. One crop that has the potential to meet these criteria is guayule (*Parthenium argentatum*). Guayule is a drought tolerant shrub native to the southwest United States and northern Mexico that has long been known as a viable source of natural rubber (Coffelt et al., 2015). Guayule's high natural rubber content, typically 8–12% by mass, makes it a potential alternative to traditional rubber sources such as petroleum and hevea trees (Rasutis et al., 2015). The relatively high value of natural rubber and the wide range of potential products such as tires, medical equipment, and performance sports apparel (wetsuits, waders) have the potential to generate revenue for farmers (Schloman, 2005; Nakayama et al., 1996; Alderson, 2016). Furthermore, other non-rubber portions of the guayule plant include a resin and the remaining lignocellulosic biomass, commonly referred to as bagasse, which can be converted into additional co-products such as liquid biofuels (Sabaini et al., 2018; Chundawat et al., 2012; Boateng et al., 2015).

Despite guayule's promising physical characteristics, its economic viability in the southwest United States remains uncertain. While renewed interest in guayule has led to some recent economic

* Corresponding author.
E-mail address: evan.sproul@colostate.edu (E. Sproul).

https://doi.org/10.1016/j.jclepro.2020.122811
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analysis, it has been limited to the conversion of guayule bagasse to fuels and the feasibility of production within Mediterranean Europe(Sabaini et al., 2018; Sfeir et al., 2014). Prior to this work, an earlier effort reviewed the costs of guayule rubber production within the United States(Weihe et al., 1979). However, this analysis is outdated and does not include current data from improved agricultural and rubber extraction processes (Foster and Coffelt, 2005; Ray et al., 2005; WagnerSchloman, 1991; Huang et al., 2018; Abdel-Haleem et al., 2019). Capturing these agricultural and rubber extraction processes in an up to date techno-economic model is essential to understanding guayule's potential for success.

In addition to a techno-economic analysis, there is a secondary need for a thorough environmental analysis of guayule rubber production. Understanding environmental impacts will allow for a comparison to other synthetic and natural rubber sources. Furthermore, it provides an opportunity to reduce the environmental impacts of guayule rubber by identifying critical areas for further research and development before production is rolled out at full-scale. Recognizing these opportunities, previous researchers have explored the environmental impacts of guayule, including a detailed sustainability review, comparison of guayule irrigation practices, and a full life cycle assessment of a guayule rubber tire (Rasutis et al., 2015; Soratana et al., 2017; Eranki et al., 2017; Eranki and Landis, 2018). Across these publications, a large amount of data exists for the agricultural production stages, but far less data exists for downstream guayule rubber extraction. In the most recent work, Eranki et al. estimated industrial scale rubber production based on an experimental solvent extraction batch process (Eranki and Landis, 2018). While this work is the only publicly available post-harvest life cycle assessment of guayule, it is limited in its analysis. For example, future industrial extraction facilities are expected to utilize a continuous solvent extraction process which has yet to be evaluated. Understanding the environmental impact of guayule rubber production at full-scale requires modeling this continuous process.

This work addresses the shortcomings of previous guayule analyses while also providing a new perspective in which economic costs and environmental impacts are integrated into a single holistic analysis. The novel innovative contributions of this work are: 1) an integrated process model that tracks all materials and energy required for present day cultivation, transportation, and extraction of guayule rubber in the southwest United States, 2) the first integrated techno-economic and environmental analysis of guayule rubber production, and 3) the identification of parameters where further research and development will reduce costs and environmental impacts. These outcomes are critical for assessing the current state of guayule rubber production. In addition, they provide guidance for the future development of guayule and similar industrial crops that may be beneficial to arid regions of the southwest United States.

2. Methods

The methods of this work are broken into three sections. The first section details the development of a process model that tracked the materials and energy required for guayule rubber production. The second and third describe how this process model was used to concurrently inform techno-economic and environmental analyses. All process modeling and analyses were developed in Microsoft Excel using Visual Basic for Applications routines to automate calculations.

2.1. Process model

The process model for guayule rubber production consisted of agricultural, transportation, and rubber extraction processes. These processes were integrated together in the process model to track cumulative material and energy demands of producing rubber, resin, and bagasse from a guayule feedstock. The process model system boundary began with field preparation for planting and ended with final production of guayule rubber and co-products. Table 1 highlights key input parameters used within the process model. A full detailed list of input parameters for the process model can be found in Tables A1-A3 of the appendix of this document. A process model diagram with a system boundary is shown Fig. 1.

2.1.1. Agricultural process

The first process of the model included all operations required to produce guayule biomass, including land preparation, planting, growing, and harvesting. Within the process there was detailed accounting of material flows such as irrigation water, fertilizers, and herbicides. From these flows, the model identified the required labor and equipment, along with corresponding energy demands in the form of fuels and electricity. The current agricultural process was modeled to represent a 500-ha farm located in central Arizona. This size was based upon the average farm size from the United States Department of Agriculture's 2018 National Agricultural Statistics for Arizona (DeWalt, 2018). The modeled farm included guayule, along with other crops such as cotton, field corn, sorghum, barley, wheat, and alfalfa. The adoption of guayule was an adjustable input parameter and was set at 15% (75 ha) of the farm for the baseline analysis. A full list of major parameters used for the agricultural process is shown in Table A1 of the appendix.

The agricultural process included a six-year guayule growth cycle. The first year of the cycle is an establishment year, meaning it includes land preparation, planting, growth, and intensive weed control until the crop has full cover. The second year is a harvest year, which includes further growth and the initial harvest of the guayule crop. When guayule is harvested in the second year, it is cut just above the ground with the root system left in the ground as a starting point for regrowth. In year three and four the shrub is regrown and harvested a second time, and years five and six repeat this pattern once more. The third harvest in year six marks the end of the growth cycle. In year seven the land is reworked and replanted, marking the beginning of a new cycle. While guayule yield does vary across different cultivation conditions, the baseline parameter used in all three harvest years was thirty metric tons per hectare with an assumed rubber fraction of 0.075 kg rubber per kg guayule biomass. These input parameters were based upon experimental data, as well as correspondence with industrial partners, and fall within the wide range of existing results and future targets for guayule rubber production reported in literature (Rasutis et al., 2015; van Beilen and Poirier, 2007).

2.1.2. Transportation process

In the transportation process of the model, harvested biomass was transported from the farms to a rubber extraction facility via short haul trucks with trailers. Total truck and trailer weight were modeled at 36,287 kg, including a 20,412 kg payload capacity. Using the information in Table 1 and geographic information system data, the average distance from the farms to an optimized processing facility location was modeled at 44.27 km. A map of this facility location and surrounding farmland suitable for guayule production in Arizona's Maricopa and Pinal counties is located in Fig. A2 of the appendix. Although the transportation distance was based on expected guayule farmland and a rubber extraction facility location in Arizona, it also aligns with transportation distances for well established markets such as corn ethanol production in the states of Iowa and Ohio (Gallagher et al., 2015). Given an operating window of 8 h per day, the model required fifteen trucks to meet the demand of the rubber extraction facility. Other transportation

Table 1
Key input parameters for process model across agriculture, transportation, and rubber extraction processes.

Key Modeling Input Parameters		
Single farm size	500	hectares
Guayule adoption	75	hectares/farm
Harvest yield	30	metric tons/hectare
Rubber fraction	0.075	kg rubber/kg biomass
Resin to rubber ratio	0.65	kg resin/kg rubber
Transport distance	44.27	km (farm to extraction facility)
Extraction input capacity	500,000	metric tons of guayule/year

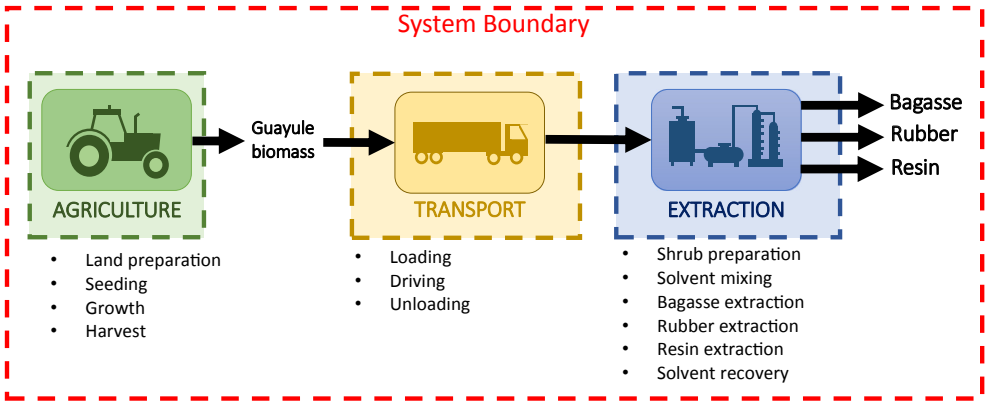


Fig. 1. Process model diagram of guayule rubber, resin, and bagasse production.

considerations included fuel efficiency, loading and unloading time, and average speed. A full list of transportation input parameters is located in Table A2 of the appendix.

2.1.3. Rubber extraction process

The third and final process in the model was a continuous rubber extraction process required to generate rubber, resin, and bagasse from the harvested guayule shrub. The model tracked the use of materials such as solvents, water, and mineral oil, along with energy in the form of natural gas and electricity. Process data was based on an existing pilot scale facility located in Arizona, as well various publications and patents (Schloman, 2005; WagnerSchloman, 1991; Huang et al., 2018). Material and energy flows were linearly scaled by mass throughput so that the model represented a full-scale facility with an input capacity of 500,000 metric tons of guayule biomass per year. The process was based on dual solvent extraction using hexane and acetone to dissolve rubber and resin, respectively. Solvent recovery was modeled in multiple distillation steps leading to overall solvent recovery efficiencies of 98.5%. Other critical input parameters considered were guayule rubber and resin content, solvent mixing ratios, and equipment efficiencies. A full list of rubber extraction input parameters and a process diagram can be found in Table A3 and Fig. A1 of the appendix.

Beyond the fundamental equipment required for rubber extraction, there were two other major modeling considerations within the rubber extraction facility. The first consideration was heat integration across the solvent recovery processes. In the model, heat exchangers reduced the high outlet temperatures leaving the recovery process by preheating the solvents, mineral oil, and water that are entering the recovery process. This reduced the consumption of natural gas required to heat flows into the recovery process and reduces the need to cool outlet flows. The effectiveness of each heat exchanger was assumed to be 85%. The second modeling consideration was the generation of on-site heat and power by combusting bagasse in a combined steam boiler and turbine system. Within the model this on-site heat and power scenario was used to burn bagasse in place of natural gas and gird electricity. In this scenario, the overall efficiency of heat generated by the steam boiler was modeled at 70%, while the overall efficiency of electricity generated by the turbine was modeled at 20% (Environmental Protec, 2007). A list of inputs for the on-site heat and power system can be found in Table A9 of the appendix.

2.2. Techno-economic analysis

The materials, energy, and equipment tracked through the process model of Section 2.1 were used to inform capital and operational costs for guayule rubber production. With this data, the techno-economic analysis was broken into two separate components. In the first, the agricultural costs were used to determine the minimum selling price of guayule biomass to recover all costs of growing guayule for six years. In the second, this guayule biomass cost, along with transportation and rubber extraction costs, were used to determine the minimum rubber selling price that would recover all production costs across the full system. The common guayule biomass selling price across the agriculture and rubber extraction processes were used to integrate the farm and rubber extraction facility into a single techno-economic analysis.

2.2.1. Agriculture economics

At the farm level, a cost benefit analysis was performed over the six-year guayule growth cycle. Agriculture costs included material and energy inputs such as fertilizer, herbicides, water, and electricity. In addition, the analysis included farm equipment and related costs such as fuel, repairs, maintenance, replacement, and labor. A full list of costs used in the baseline scenario is included in Tables A4-A6 of the appendix. Due to the six-year time frame, it was necessary to discount future costs back to their present value using a discount factor. The baseline discount rate defined for the farm was 6%. This discount rate and other parameters used for the

baseline agriculture economic analysis are listed in Table 2. With these parameters, the agriculture economic analysis was solved to find the minimum selling price of the guayule biomass that would allow revenue to recover all guayule agriculture costs over the six-year period.

2.2.2. Rubber extraction economics

The minimum selling price of guayule biomass from the farm also represents the minimum biomass purchase price for the rubber extraction facility. This biomass cost was combined with other operating costs, capital costs, transportation costs, and product revenues into a single techno-economic analysis for the full 30-year lifetime of the rubber extraction facility. The techno-economic analysis was built around a set of standard parameters based on previous bioprocessing publications (Humbird et al., 2011; Davis et al., 2014; Dutta et al., 2011; Swanson et al., 2010). All process facility costs are shown in Tables A7 and A8 of the appendix with key parameters used in the techno-economic analysis presented in Table 2. The rubber extraction techno-economic analysis was solved to find the minimum selling price of rubber that would yield a total net present value of zero at the end of the thirty-year life time. This minimum selling price represents the revenue needed to recover all costs of production including agriculture, transportation, and rubber extraction.

2.2.3. Scenarios and sensitivity in techno-economic analysis

Recognizing that the minimum selling price of rubber is dependent upon co-products, two different co-product scenarios were analyzed. The first was the baseline scenario where co-product revenue is generated by selling bagasse at $0.10 per kg and resin at $1.00 per kg. These co-product values align with a previous analysis when adjusted for inflation to 2020 US dollars (Weihe et al., 1979). The second scenario used the bagasse to generate on-site heat and power, instead of selling bagasse as a co-product. In this scenario, the capital cost of the on-site heat and power system (including installation, indirect, and contingency costs) was estimated at $1300 per kW of combined heat and power capacity (Kumar et al., 2003). Maintenance of the system was estimated at 3% of the capital cost and labor included eight additional shift operators. In situations where bagasse production exceeded the heat and power requirements for rubber extraction, excess electricity was treated as a co-product and was sold back to the grid at a rate of $0.05 per kWh. This rate is relatively conservative when compared to current rates offered to Arizona power customers with on-site solar installations (Hobbick, 2019). In the on-site heat and power scenario, the value of resin was kept at $1.00 per kg.

The final component of the techno-economic analysis was a sensitivity analysis. The sensitivity analysis was performed by varying 147 individual input parameters by ±20%. As each parameter was varied, the new minimum rubber selling price was recorded. Once the results of all parameters were recorded, the list was sorted to identify the individual input parameters that have the largest impact on the economic results of the model.

Table 2
Input parameters for techno-economic analysis.

Agriculture Economic Input Parameters	
Discount rate	6%
Miscellaneous and overhead as a percent of cash costs	5%
Operating interest rate for harvest operations	8%
Operating interest rate for production inputs	8%
Duration of harvest loan	6 months
Duration of operating loan	6 months
Rubber Extraction Economic Input Parameters	
Rubber Extraction Facility Loan and Investment	
Internal rate of return	10%
Equity	40%
Loan interest	8%
Loan term	10 years
Rubber Extraction Facility Construction	
Working capital	5%
Construction period	3 years
Construction completed year −2	10%
Construction completed year −1	50%
Construction completed year 0	40%
Rubber Extraction Facility Start Up	
Startup time	0.5 years
Production during start up	50%
Rubber Extraction Facility Taxes and Depreciation	
Tax rate	35%
Depreciation	7 year MACRS

2.3. Environmental analysis

2.3.1. Scope and data of environmental analysis

Similar to the techno-economic analysis, the environmental analysis was informed by the process model outlined in Section 2.1. The environmental analysis focused on identifying the cradle-to-gate environmental impacts of guayule rubber production via life cycle assessment methods (International Standards O, 2006a; International Standards O, 2006b). Emissions due to upstream materials and energy (i.e. those that were consumed throughout the supply chain) were obtained from ecoinvent 3.4 and the United States Life Cycle Inventory database (Wernet et al., 2016; National Renewable Energy, 2012). A full list of life cycle inventory data can be found in Tables A10 and A11 of the appendix. Per standard life cycle assessment cut-off methods, the environmental impacts embodied within capital infrastructure (e.g. steel, concrete) were excluded from this analysis due to their minimal impact when spread over a thirty-year operational period (International Standards O, 2006b). However, embodied emissions were included for farm equipment as the lifetime of this equipment is often far less than thirty years, making the embodied impacts more significant. Cumulative emissions for guayule rubber production were grouped into ten categories of environmental impacts via the United States Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1 (Bare, 2011).

2.3.2. Scenarios and allocation in environmental analysis

Within the environmental analysis, the baseline and on-site heat and power scenarios were both considered. In the baseline scenario the environmental impacts of rubber, resin, and bagasse were summed to generate a total system environmental impact. Within the on-site heat and power scenario, bagasse is combusted to replace natural gas and grid electricity consumption. In addition, any excess electricity from bagasse was modeled to displace standard grid electricity, resulting in an environmental impact credit that was applied to the overall rubber and resin production process. Estimating the individual environmental impacts of rubber, resin, and bagasse required allocating some portion of the total environmental impact to each product.

While allocation helps isolate the impacts of specific products, it can also significantly alter results, leading to different conclusions. As a result, two forms of allocation were applied to present two separate perspectives. The first was mass allocation, which distributes the share of environmental impacts across products based upon the overall mass of each product. The second was economic

allocation, which distributes the environmental impacts based on the economic value of each product. While economic allocation is accompanied by uncertainty, it is considered a common practice in LCA when other methods such as expansion of the system boundary are not an option (Ardente and Cellura, 2012). In addition, it has been found as a valuable form of analysis when co-products have significantly different economic values, as is the case with guayule rubber, bagasse, and resin. Mass and economic methods for allocating the environmental impacts to a specific product are shown in Equations (1) and (2), respectively.

$$Environmental\ Impact_{mass,p} = (Environmental\ Impact_t)\frac{Mass_p}{Mass_t} \quad (1)$$

$$Environmental\ Impact_{economic,p} = (Environmental\ Impact_t)\frac{Economic\ Value_p}{Economic\ Value_t} \quad (2)$$

In Equation (1), a portion of the total (t) environmental impact of the system is allocated to a specific product (p) based on the product's mass relative to the total mass of all products. In Equation (2), a portion of the total environmental impact of the system is allocated to a specific product based on the product's economic value relative to the total economic value of all products.

3. Results

Results are broken into two sections corresponding to the techno-economic and environmental analyses. All economic and environmental results across the two sections are coupled via the common process model which tracked materials and energy required for the production of rubber, resin, and bagasse. The economic and environmental results considered two scenarios: 1) the baseline scenario in which bagasse and resin are sold at predefined values and 2) the on-site heat and power scenario in which bagasse is combusted to generate heat and electricity.

3.1. Techno-economic analysis

The economic results of the baseline scenario are displayed in Fig. 2. The figure includes the baseline minimum selling price of rubber at $3.08 per kg along with corresponding costs and revenues. Total costs ($4.91 per kg) are broken down to show major contributions from operations within agriculture ($1.82 per kg of rubber) and rubber extraction ($3.09 per kg of rubber). Within agriculture the largest overall cost was irrigation which required $0.65 per kg of rubber. The next major contributors to agricultural cost were equipment with fuels and maintenance at $0.52 per kg of rubber and plant fertilizers and herbicides at $0.43 per kg of rubber. Other minor items such as insurance and taxes combine to make up the remaining agricultural cost of $0.22 per kg. Within the rubber extraction, the largest individual cost contributors were capital/loan, solvents, and natural gas at $0.91, $0.63, and $0.40 per kg of rubber, respectively. The "other processing" category included costs from labor, maintenance, electricity, mineral oil, insurance, and water, all of which contributed less than $0.17 per kg of rubber individually, but sum to a total of $1.12 per kg of rubber. Transportation had a minimal impact of $0.02 per kg due to the relatively short transport distance of 44 km between the farm and the rubber extraction facility.

The alternative on-site heat and power scenario in which bagasse is combusted to replace electricity and natural gas consumption is also presented in Fig. 2. In this scenario the minimum selling price was $4.07 per kg, an increase of 32% from the baseline scenario. This higher price was due to increased capital and loan costs from the purchase and installation of the combined boiler and turbine system. These results are clearly illustrated within Fig. 2 in which the capital/loan costs of on-site heat and power are 164% that of the baseline scenario. In addition to this cost, the bagasse revenue of the baseline system was removed, increasing the rubber selling price further. The combined heat and power scenario did have the positive impact of removing the costs of natural gas and grid electricity, as well as generating revenue through the sale of excess electricity. However, the current low cost of natural gas and electricity lead to overall modest savings that did not offset the capital costs required for the heat and power system.

Results from the ±20% sensitivity analysis performed on the baseline scenario are shown in Fig. 3 with an expanded list shown in Fig. A2 of the appendix. Unsurprisingly, the rubber fraction of the guayule biomass had the largest impact of any variable on the minimum selling price as rubber mass is the functional unit of the techno-economic analysis. The second highest impact variable was harvest yield. Although harvest yield had minimal impact on rubber extraction costs, it did have a large impact on overall agricultural costs. Other high impact parameters in the top ten are related to solvents, co-product revenue, and equipment costs. These variables align with the baseline results of Fig. 2 in which solvents, capital costs, and co-product revenues were found to have large contributions to overall cost. The other remaining parameters in the top ten are harvest area and resin to rubber ratio, which had impacts on agricultural costs and expected resin revenue, respectively. Two notable parameters outside the top ten are natural gas and electricity costs. The lower sensitivity of these parameters agrees with the on-site heat and power scenario in Fig. 2 where replacing natural gas and grid electricity with bagasse did not outweigh the added capital costs of a boiler and turbine system.

3.2. Environmental analysis

The environmental impacts of rubber, resin, and bagasse production are displayed in Table 3. These impacts include all burdens of the materials and energy consumed across agriculture, transportation, and rubber extraction. For example, the environmental impacts of natural gas used in solvent extraction included extraction from a well site, refining, distribution, and combustion. For the baseline scenario, the total impacts were distributed across rubber, bagasse, and resin using both mass and economic allocation. For the on-site heat and power scenario, a credit was given for excess electricity that was sold back to the grid, then the remaining impacts were allocated across rubber and resin based on mass and economic allocation.

The relative contributions of different operations to total environmental impacts across all categories are shown in Fig. 4. These contributions include agriculture (green), transportation (yellow),

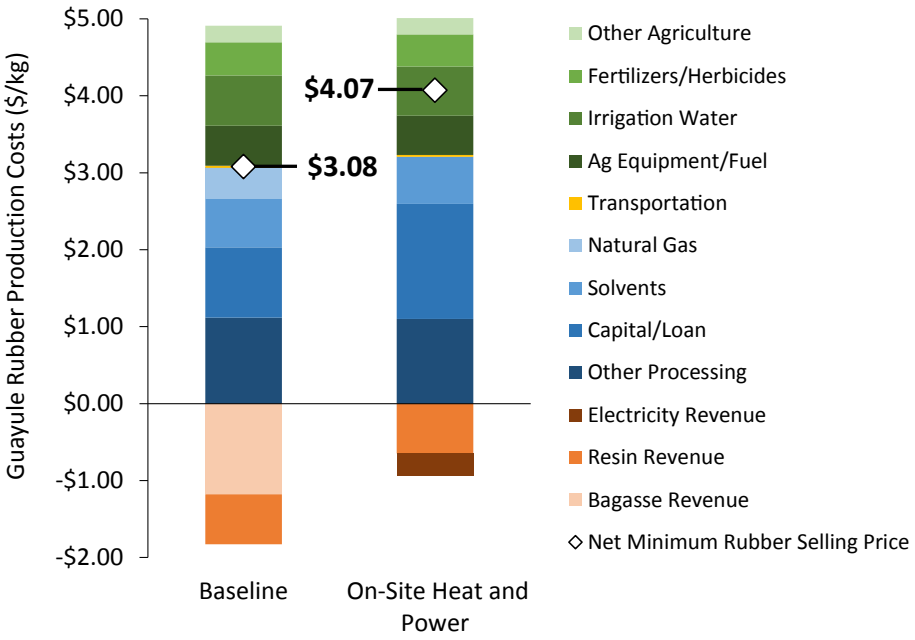


Fig. 2. Minimum guayule rubber selling price required for a net present value of zero over thirty years of production. Production costs are shown for agriculture (green), transportation (yellow), and rubber extraction (blue). The baseline scenario includes co-product revenues (orange) of $1.00 per kg resin and $0.10 per kg bagasse. The on-site heat and power scenario includes co-product revenue of $1.00 per kg of resin and $0.05 per kWh of excess electricity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

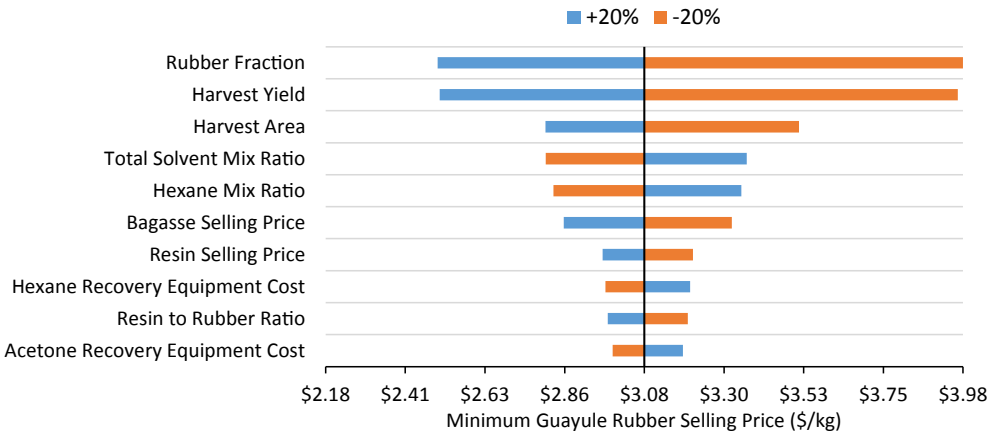


Fig. 3. Change in baseline scenario minimum rubber selling price due to varying individual input parameters by ±20%. The ten parameters with the largest impact are shown here, with an extended list of parameters shown in Figure A2 of the appendix.

and rubber extraction (blue). Across the ten categories, agriculture ranged from 13% to 45% of the total environmental impact, while the rubber extraction process made up between 52% and 87% of the overall impact. Similar to techno-economic results, transportation had an overall impact less than 3% across all categories due to minimal transportation distances between the farm and the rubber extraction facility. Within agriculture, fertilizer application had the largest impact across the majority of categories, followed by irrigation which uses a large amount of electricity for water pumping. Within rubber extraction, the largest overall impacts came from solvent mixing, resin extraction, and solvent recovery. The large impact of solvent mixing was due to high solvent flow rates coupled with the upstream environmental impacts of producing solvents. The impact of resin extraction and solvent recovery was due to large quantities of natural gas used to distill and purify the components of the resin-solvent mixture. This distillation enables the sale of a pure resin co-product and the reuse of solvents within the extraction process, avoiding the need for additional make-up solvent which would increase environmental burden.

4. Discussion

The results of Sections 3.1 and 3.2 lead to four major points of discussion that are covered in detail below: 1) the current estimate of a minimum guayule selling price is on the high end of hevea rubber prices, but it can be reduced via the three key parameters of biomass yield, rubber content, and resin co-product value, 2) the value and fate of co-products, most notably the resin, represents a large source of uncertainty warranting further research and development, 3) current global warming emission results are similar to hevea rubber production, but the end use of bagasse and LCA allocation methods have a large impact on the environmental

Table 3
TRACI 2.1 environmental impacts of guayule rubber, resin, and bagasse produced by 1 ha of farm. Total impacts are aggregated across agriculture, transportation, and rubber extraction. Impacts in both scenarios are allocated by mass and economic methods. The on-site heat and power scenario includes a credit for excess electricity sold back to the grid.

			Acidification (kg SO_2 eq)	Ecotoxicity (CTUe)	Eutrophication (kg N eq)	Global Warming (kg CO_2 eq)	Human Health Carcinogenics (CTUh)	Human Health Non Carcinogenics (CTUh)	Ozone Depletion (kg CFC-11 eq)	Photochemical Ozone Formation (kg O_3 eq)	Resource Depletion Fossil Fuels (MJ Surplus)	Respiratory (PM 2.5 eq) Effects
Baseline	Impacts per hectare		6.37E+01	5.49E+04	6.36E+01	1.98E+04	6.52E-04	2.36E-03	2.10E-03	9.39E+02	3.99E+04	1.90E+01
	Mass Allocation (per hectare)	Rubber	4.73E+00	4.08E+03	4.73E+00	1.47E+03	4.84E-05	1.75E-04	1.56E-04	6.98E+01	2.97E+03	1.41E+00
		Bagasse	5.58E+01	4.82E+04	5.58E+01	1.74E+04	5.72E-04	2.07E-03	1.84E-03	8.23E+02	3.50E+04	1.66E+01
		Resin	3.08E+00	2.65E+03	3.08E+00	9.58E+02	3.15E-05	1.14E-04	1.01E-04	4.54E+01	1.93E+03	9.17E-01
	Economic Allocation (per hectare)	Rubber	3.91E+01	3.37E+04	3.91E+01	1.22E+04	4.00E-04	1.45E-03	1.29E-03	5.76E+02	2.45E+04	1.16E+01
		Bagasse	1.58E+01	1.37E+04	1.58E+01	4.93E+03	1.62E-04	5.86E-04	5.22E-04	2.34E+02	9.93E+03	4.72E+00
		Resin	8.72E+00	7.53E+03	8.72E+00	2.72E+03	8.93E-05	3.23E-04	2.88E-04	1.29E+02	5.47E+03	2.60E+00
On Site Heat and Power	Impacts per hectare		7.98E+01	2.93E+04	5.35E+01	7.77E+03	1.02E-02	1.96E-03	7.53E-03	1.81E+03	1.73E+04	3.09E+01
	Electricity Credit		1.25E+01	3.08E+04	4.10E+01	5.43E+03	4.30E-04	1.22E-03	4.10E-04	1.76E+02	4.41E+03	1.49E+01
	Impacts Minus Credit		6.72E+01	−1.49E+03	1.25E+01	2.35E+03	9.78E-03	7.36E-04	7.12E-03	1.63E+03	1.29E+04	1.60E+01
	Mass Allocation (per hectare)	Rubber	4.07E+01	−9.03E+02	7.58E+00	1.42E+03	5.93E-03	4.46E-04	4.32E-03	9.89E+02	7.84E+03	9.69E+00
		Resin	2.65E+01	−5.87E+02	4.93E+00	9.25E+02	3.85E-03	2.90E-04	2.80E-03	6.43E+02	5.10E+03	6.30E+00
	Economic Allocation (per hectare)	Rubber	5.80E+01	−1.28E+03	1.08E+01	2.03E+03	8.43E-03	6.35E-04	6.14E-03	1.41E+03	1.12E+04	1.38E+01
		Resin	9.25E+00	−2.05E+02	1.72E+00	3.23E+02	1.35E-03	1.01E-04	9.80E-04	2.25E+02	1.78E+03	2.20E+00

results, and 4) results of this work can be compared with previous analysis for validation, but the results of this study move beyond previous work and advance our understanding of guayule rubber production and future opportunities.

4.1. Economic comparison to hevea rubber

The success of guayule rubber in the southwest United States is largely dependent upon the economics of production. A direct comparison of the economic results from this study to the current market values for two existing types of hevea rubber is presented in Fig. 5. In the figure, the baseline minimum selling price of $3.08 per kg of guayule rubber found in this study is within the bounds of hevea rubber market values over the past ten years (RubberS3 Futures Histo, 2019; RubberR20 Futures Hist, 2019). However, it lands in the upper 25th percentile of values, meaning at this price point it is typically more expensive than hevea rubber. Improving key performance parameters could reduce the price of guayule rubber to be within the inner 50th percentile of market values, making it more competitive with hevea rubber. As demonstrated in the sensitivity analysis (Fig. 3), two parameters that have a large impact on selling price are the agricultural harvest yields and the rubber content of guayule biomass. Improving these parameters, along with the resin co-product value through further research and development could reduce the minimum required selling price of guayule rubber. For example, in Fig. 5, the agricultural harvest yield was increased from 30 to 32 metric tons per hectare, the rubber content was increased from 7.5% to 8.5%, and the resin value was increased from $1.00 to $2.00 per kilogram of resin. Solving the model with these new input values resulted in a minimum selling price of $1.91 per kg of guayule rubber, a 38% decrease from the baseline value of $3.08 per kg of rubber. The proposed increases represent optimistic but realistic potential future performance. This new value falls within the inner 50th percentile of existing market prices, meaning is guayule more competitive with hevea.

4.2. The importance and uncertainty of co-products

Resin and bagasse co-products will play an important role in the economic viability of guayule rubber (Jara et al., 2019; Audu et al., 2019). In order to highlight the impact of co-products, the variation of minimum rubber selling price as a function of resin and bagasse value is presented in Fig. 6. When bagasse is sold at the baseline value of $0.10 per kg and resin is varied from $0-$3.00 per kg, the minimum selling price of rubber ranges from $3.72 per kg down to $1.82 per kg. The large impact of resin value on rubber selling price is largely because rubber and resin make up similar quantities of the guayule biomass. Therefore, these two products have similar impacts on revenue and corresponding economic viability. This reflects the importance of the resin, which remains the least certain value in this techno-economic analysis. Reducing uncertainty through future resin application research is critical to the success of guayule as a natural rubber feedstock.

The relatively well-established pathways from lignocellulosic biomass to biofuels makes the value of the bagasse more defined than the resin. For example, the previous techno-economic analysis of guayule bagasse pyrolysis places the value of bagasse at $0.052 per kg (Sabaini et al., 2018) and the study of guayule rubber production in the Mediterranean puts bagasse at $0.11 per kg (Sfeir et al., 2014). Given these data points as well as earlier estimates (Weihe et al., 1979), it is unlikely guayule bagasse will greatly exceed a value of the $0.15 per kg, used in this work to represent a high end estimate. As shown in Fig. 6, increasing the bagasse value from $0.10 to $0.15 per kg reduces the minimum selling price of rubber by $0.59 per kg. The alternative to selling guayule bagasse is

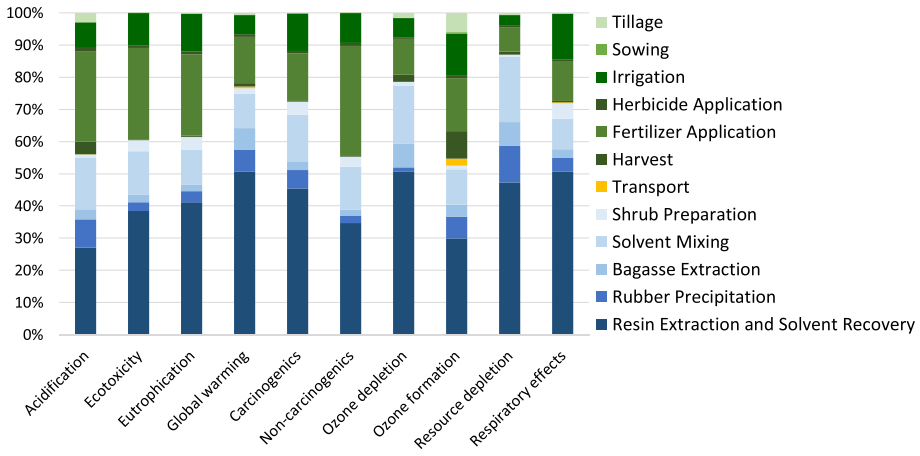


Fig. 4. The relative contributions of TRACI 2.1 environmental impacts for the baseline scenario broken out by agriculture (green), transportation (yellow), and rubber extraction (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

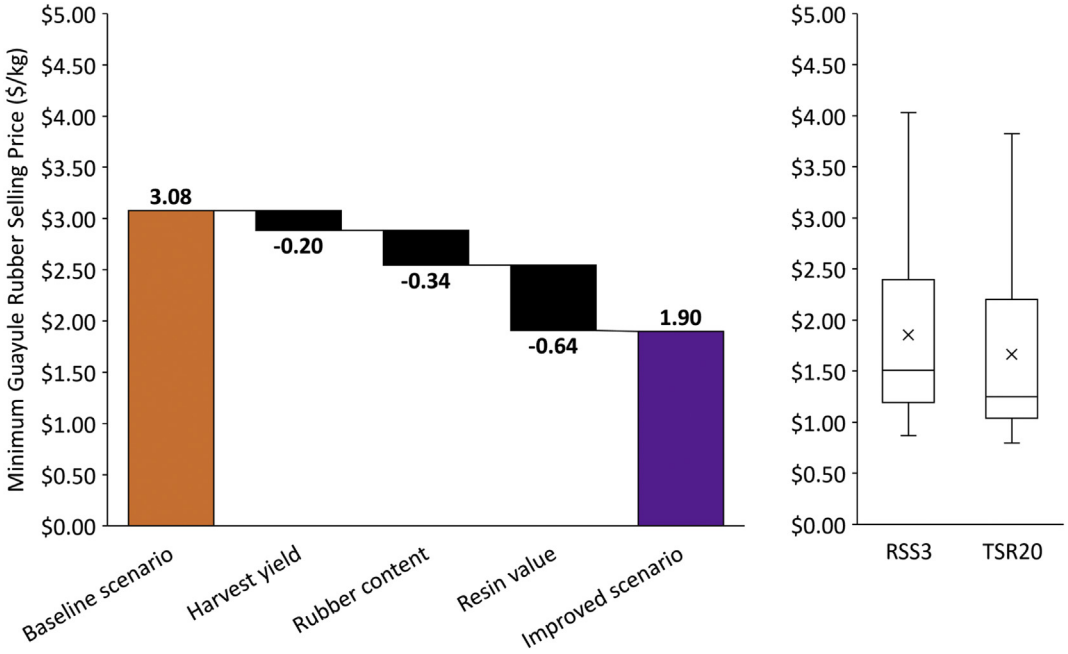


Fig. 5. (Left) Change in minimum selling price from baseline scenario at $3.08 per kg to improved scenario at $1.91 per kg. The improved scenario includes increasing harvest yield to 32 metric tons per hectare, increasing rubber content to 8.5%, and increasing resin value to $2.00 per kg. Black bars represent the individual impact of each variable, while the purple bar represents the cumulative impact of all three variables. (Right) Market values for Ribbed Smoked Sheets (RSS3) and Technically Specified Rubber (TSR20) on the Singapore Exchange. Market price distributions are based on monthly prices from December of 2009 through November of 2019 (RubberS3 Futures Histo, 2019; RubberR20 Futures Hist, 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

on-site combustion to produce electricity and heat. Combusting the bagasse in this scenario is less complex than the logistics of biofuel production. However, the relatively low costs of natural gas and electricity, as well as the increase in capital cost leads to the overall cost increase shown in Fig. 6.

4.3. The impact of scope, allocation, and on-site heat and power on global warming results

There are a range of economic considerations that can alter the costs and benefits of guayule production. Similarly, there are a broad range of considerations that can shape the environmental impacts of guayule based products. Critical considerations included in this analysis were the selection of an allocation method, and the use of bagasse for heat and power. The effect of these considerations on global warming are presented in Table 4A. In the baseline scenario, the global warming of guayule rubber varies from 0.77 to 6.48 kg CO_2 eq per kg rubber depending upon allocation method. The low end of this range is the result of the large mass of bagasse which is allocated the majority of environmental burden in the mass allocation method. This allocation of burden to bagasse is beneficial from the perspective of rubber production. However, the large bagasse burden must be accounted for in downstream production of products such as biofuels, which is likely to make those products environmentally unattractive. The alternative perspective of economic allocation balances out the large mass of bagasse with its relatively low economic value, which in turn increases the impact of rubber to 6.48 kg CO_2 eq per kg rubber.

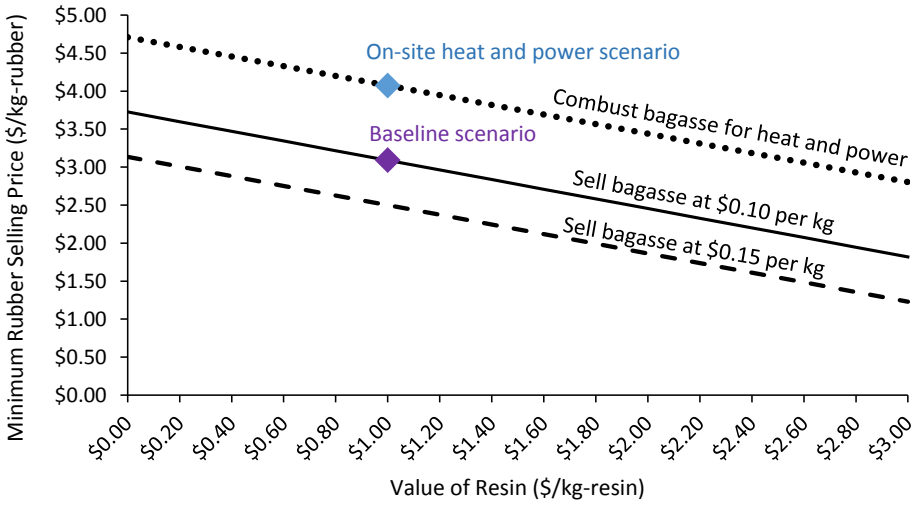


Fig. 6. Variation of minimum rubber selling price as a function of the value of resin. Diagonal lines represent different bagasse scenarios, one where bagasse is combusted for on-site heat and power and two others where bagasse is sold at values of $0.10 per kg (baseline) and $0.15 per kg. Diamond markers represent the baseline (purple) and on-site heat and power (blue) results of Section 3.1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The large difference between mass and market allocation results in the baseline scenario makes it difficult to conclude the true environmental impact of guayule rubber. Following standard LCA practice by increasing the system boundary to include the end use of rubber, resin, and bagasse would alleviate the need for allocation. However, doing so would require defining the end use of all products, which at this point is highly uncertain. Considering this limitation, both allocation results are presented, with market allocation deemed the preferred option as it is less biased by the large mass ratio of bagasse to resin and rubber. The on-site heat and power scenario shows far less variability between allocation methods as the rubber and resin products have similar masses. Therefore, the choice between allocation methods for on-site heat and power is not critical to the overall outcome. Table 4B also includes global warming estimates for synthetic Styrene Butadiene Rubber (SBR) and hevea rubber, which are explained in greater detail in the appendix.

It is important to note that consideration of direct field emissions from agricultural practices and alternative (drip or sprinkler) irrigation practices were excluded from this analysis. Field emissions were not included as the data does not exist, meaning current results may underestimate agricultural impacts related to water and air quality. These emissions are expected to be included in future modeling efforts as data becomes available. Conversely, there is already a large amount of data relating to the impacts of irrigation, which can present widely different environmental results based on the type and amount of water applied (Eranki et al., 2017). Given the already broad scope of this integrated analysis, a single irrigation method (surface flood) was selected as it reflects the least complex and most common method used for guayule cultivation in the United States.

4.4. Comparison to existing literature

The lack of previous research on guayule economics makes comparing the results of this study to previous work challenging. However, the previous analysis of a guayule production chain in the Mediterranean does serve as a reference point (Sfeir et al., 2014). In one scenario of that analysis, crude rubber, latex, resin, and bagasse were produced, with inputs of 5.9%, 2.2%, 9.0%, and 75% of biomass, respectively. The analysis resulted in selling prices of $2.38, $2.73, $2.34, $0.11 per kg for crude rubber, latex, resin, and bagasse, when converted to U.S. dollars. Although, the production of latex and crude rubber differs from the rubber extraction in this analysis, these results can be roughly compared with the improved scenario considered in Fig. 5, which uses similar input parameters and results in a guayule rubber selling price of $1.91 per kg. The comparison does provide some initial validation of overall model results, but does not confirm many specific assumptions. Significant differences in the foundational biomass production and extraction process makes further exploration of differences unrealistic.

Within the environmental analysis, the total global warming results of the baseline scenario (10.3 kg CO_2 eq per kg of rubber) compare favorably with results from the previous life cycle assessment (13.8 kg CO_2 eq per kg of rubber produced) (Soratana et al., 2017). In addition to the baseline scenario, previous studies have also evaluated the generation of electricity by combusting bagasse. In general, these studies have demonstrated a significant reduction in global warming emissions, as combustion of biomass typically results in lower emissions than electricity sourced from the grid (Soratana et al., 2017; Eranki and Landis, 2018). While the current on-site heat and power scenario also finds a reduction of

Table 4
(A) Global warming of guayule rubber production for baseline and on-site heat and power scenarios allocated by mass and economics. (B) Estimated global warming values for domestic synthetic styrene butadiene rubber (SBR) (Soratana et al., 2017; Wernet et al., 2016; Argonne National Laborato, 2018) and ribbed smoked sheets (RSS3) produced in Thailand (Jawjit et al., 2010).

A. Global Warming of Guayule Rubber Production			B. Global Warming of Standard Rubber Production	
kg CO_2 eq/kg guayule rubber			kg CO_2 eq/kg rubber	
	Baseline	On Site Heat and Power	Synthetic Rubber	3.05
Mass allocation	0.77	0.74	Hevea Rubber	0.91
Economic Allocation	6.48	1.05		

global warming emissions, it takes the analysis a step further to include the increase in overall cost resulting from bagasse combustion in an expensive boiler and turbine system. As a result, the on-site heat and power scenario in this integrated analysis has highlighted the important economic and environmental tradeoffs that can occur during process development. As development of guayule continues, these tradeoffs should be evaluated to better understand the impact of future decisions and optimize a path toward reducing both costs and environmental impacts.

5. Conclusions

This work is the first concurrent economic and environmental analysis of a guayule rubber production. The foundation of the work is constructed on a detailed process model that accurately captures all materials and energy requirements for producing guayule and co-products in the southwest United States. Key findings from the work included the economic and environmental impact of guayule production, as well as future directions for further research and development. The current baseline estimate for the minimum selling price of guayule rubber is on the high end of the existing hevea rubber market. As a result, future research should be focused on improving parameters that can reduce costs and increase rubber production. Parameters that could have a large impact are the harvest yield, biomass rubber content, and resin value. Furthermore, within the techno-economic analysis, the value of the resin represents the largest source of uncertainty, making future research and development of resin essential to the overall economic viability of guayule. An alternative processing scenario considered in this work was combusting bagasse for on-site heat and power to displace natural gas and grid electricity consumption. While this does increase the overall cost of production, it also reduces the global warming emissions of rubber production. This sort of reduction can make global warming emissions of guayule rubber competitive with other natural and synthetic rubber sources. Further modeling and analysis can be used to better understand these economic and environmental tradeoffs, while also identifying new scenarios and pathways to improve the economic viability and environmental impacts of guayule.

Funding

Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture. USDA-NIFA Grant Number: 2017-68005-26867.

CRediT authorship contribution statement

Evan Sproul: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Hailey M. Summers:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization. **Clark Seavert:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - review & editing. **Joram Robbs:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - review & editing. **Sita Khanal:** Validation, Formal analysis, Investigation, Writing - review & editing. **VeeAnder Mealing:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - review & editing. **Amy E. Landis:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Neng Fan:** Methodology, Validation, Formal analysis, Investigation, Writing - review & editing. **Ou Sun:** Methodology, Validation, Formal analysis, Investigation. **Jason C. Quinn:** Conceptualization, Methodology, Resources, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

The authors thank Robert White, David Dierig, Michael Hartzell, and Mark DeDecker of Bridgestone for their input. The authors also gratefully acknowledge support from other collaborators within the Sustainable Bioeconomy for Arid Regions project (https://sbar.arizona.edu/).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.122811.

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