Integrating economic, environmental, and social impacts into optimal design of a biomass supply chain for semi-arid areas

agricultural operations management in semi-arid areas

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Guayule and Guar

- Drought-tolerant and low-water-use crops
- Great potential for the agricultural economy of the Southwestern U.S.
- Sustainable Bioeconomy for Arid Regions (SBAR) https://sbar.arizona.edu
  (5-year project with a $15 million dollar grant from the USDA-NIFA)

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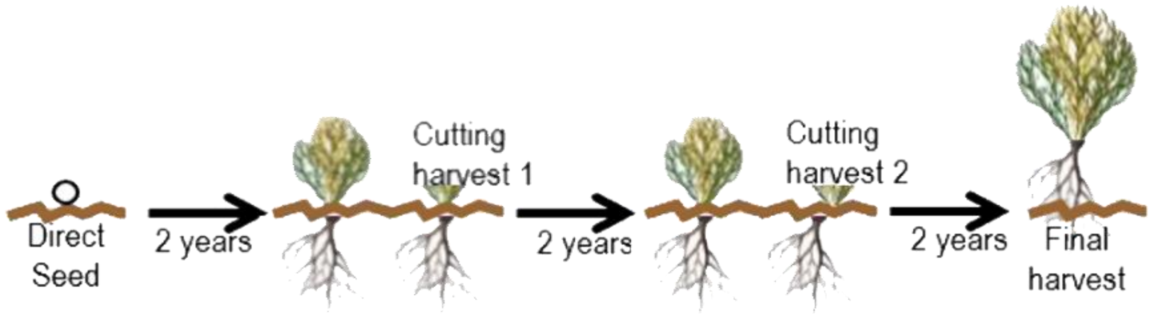
Guayule

United States Department of Agriculture

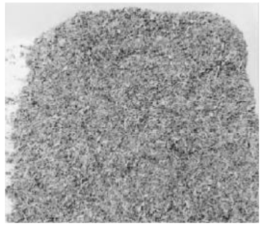
National Institute of Food and Agriculture



Guayule

- A perennial 6-year woody shrub which takes approximately 18 months to 2 years to reach harvest size
- Harvest guayule every 2 years within the 6-year period
- Intermediate harvests are possible at the end of year one, but the highest rubber content is found in year two harvests
- A reliable domestic source of natural rubber

Guayule Rubber (Source: Bridgestone)



Guayule Bagasse
Source: G.A. Holt et. al, 2012

Guayule Rubber (Source: google)

Guayule Resin (%)
Source: S.M. Lusher Dissertation, 201[illegible]

Guar

United States Department of Agriculture
National Institute of Food and Agriculture

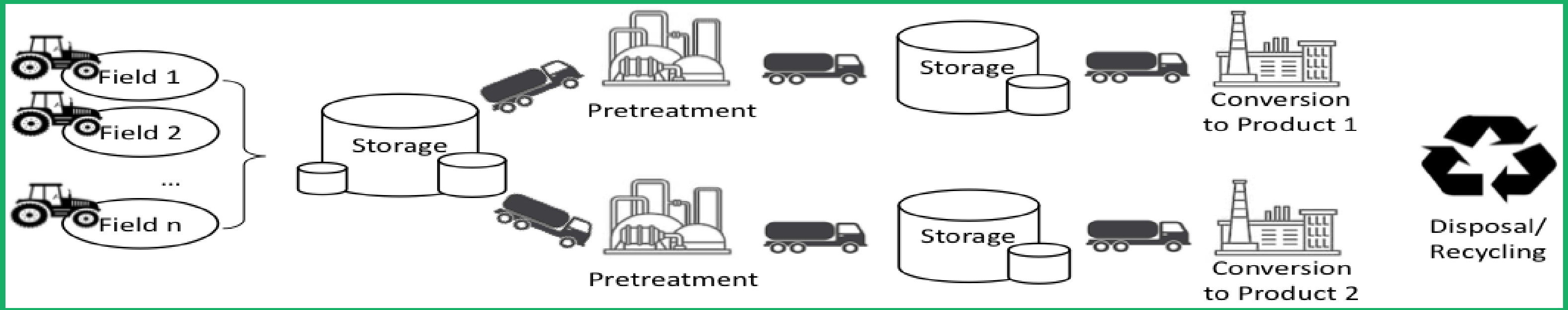
Guar

- Drought-tolerant and sun-loving, but it is susceptible to frost
- Requires sufficient soil moisture before planting and during maturation of seeds
- Frequent drought periods can lead to delayed maturation
- An annual legume and the source of guar gum (extracted from guar beans)
- Guar gum and its derivatives are essential in several fields such as pharmaceutical, petroleum, paints, batteries, cosmetics, textiles, ceramics, food, agriculture, and many others

Biomass Supply Chains for Guayule and Guar

Biomass Supply Chains for Guar and Guayule

Physical Level



Decision Support Modules

Smart Farm Production and Scheduling
- Farm Production Planning
- Equipment Scheduling
- Harvest Scheduling

Smart Facility Planning and Transportation
- Facility Location
- Capacity Planning
- Shipment Scheduling
- Transportation Mode Choice and Routing

Smart Sustainability and Economics Analysis
- Regional Economics
- Social Impacts

Model and Algorithm Library

Optimization: stochastic programming and robust optimization

Statistical Machine Learning: supply and demand forecasting

LCA: life cycle assessment

Data and Information

Stakeholders: Bridgestone, farmers, end customers; third party logistics; local utility suppliers; government and policy makers; USDA

GIS (Geographic information system): Google map, NRCS@USDA

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Instruction Manual for Integrated Optimization Modules

SBAR

USDA United States Department of Agriculture | National Institute of Food and Agriculture

SUSTAINABLE BIOECONOMY
FOR ARID REGIONS

SBAR

Biomass Supply Chain and Transportation:
Instruction Manual

THE UNIVERSITY OF ARIZONA

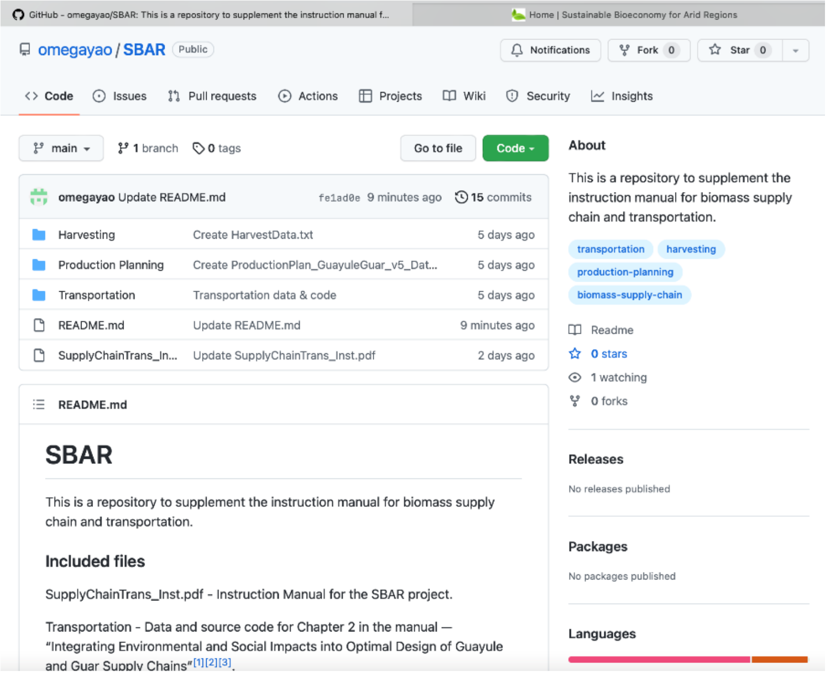
SYSTEMS AND INDUSTRIAL ENGINEERING DEPARTMENT

By

Daniel A. ZUNIGA VAZQUEZ, Shunyu YAO, Neng FAN

July 25, 2022

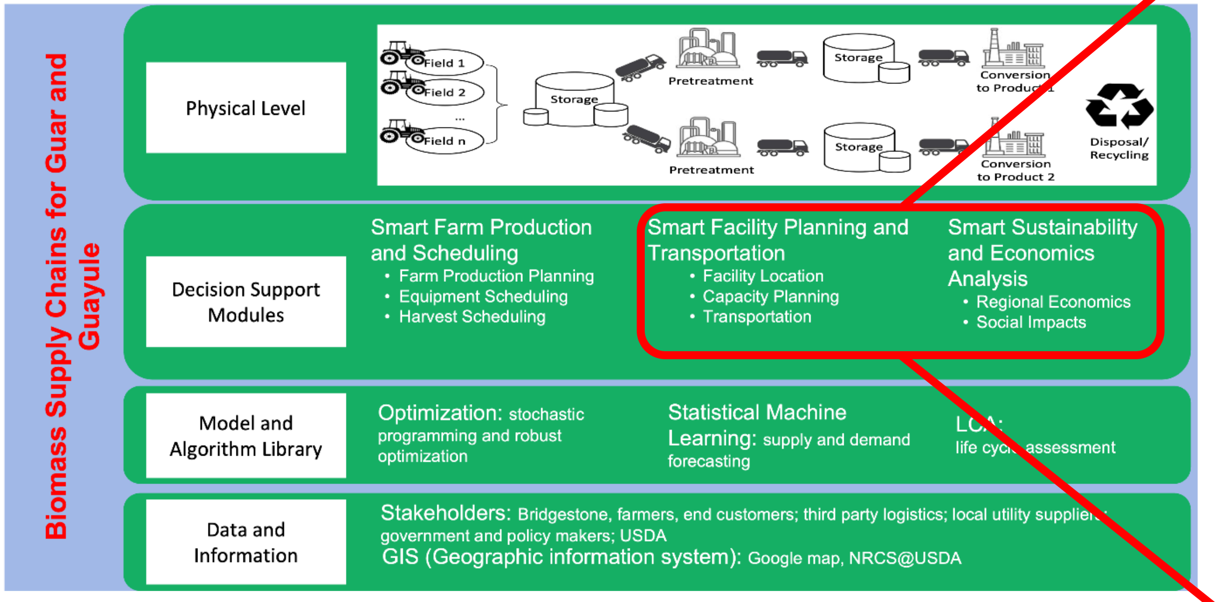
Contents

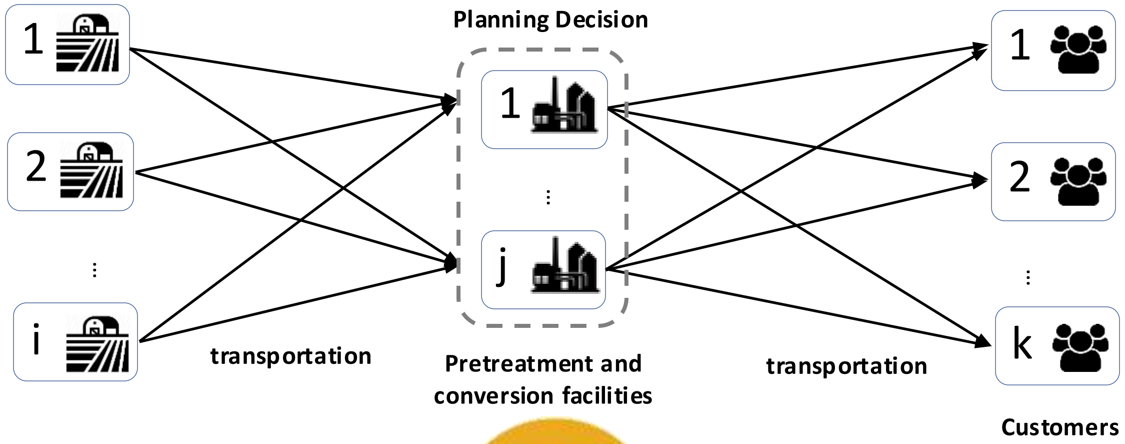


- The full instruction manual is available at https://github.com/omegayao/SBAR
- The data, computer code, and relevant information are all stored in Github.

Module I - Facility Location and Transportation

United States Department of Agriculture
National Institute of Food and Agriculture





$$\min_{x,cap,u,v} \underbrace{\theta^1 EcoBen}_{\text{Economical}} + \underbrace{\theta^2 EnvImp}_{\text{Environmental}} + \underbrace{\max \theta^3 SocImp}_{\text{Social}}$$

- Zuniga Vazquez, D., Sun, O., Fan, N., Sproul, E., Summers, H., Quinn, J., Khanal, S., Gutierrez, P., Mealing, V., Landies, A., Seavert, C., Teegerstrom, T., & Evancho, B. (2021). Integrating environmental and social impacts into optimal design of guayule and guar supply chains. *Computers & Chemical Engineering*, 146, 107223. doi:10.1016/j.compchemeng.2021.107223
- D. A. Zuniga Vazquez, N. Fan, T. Teegerstrom, C. Seavert, H.M. Summers, E. Sproul, and J.C. Quinn (2023). Optimal Design of Guayule and Guar Supply Chains for the American Southwest *Proceedings of the IISE Annual Conference & Expo 2023.*
- Sproul, E., Summers, H., Seavert, C., Robbs, J., Khanal, S., Mealing, V., Landies, A., Fan, N., Sun, O., & Quinn, J. (2020). Integrated techno-economic and environmental analysis of guayule rubber production. *Journal of Cleaner Production*, 273, 122811. doi:10.1016/j.jclepro.2020.122811
- Summers, H., Sproul, E., Seavert, C., Angadi, S., Robbs, J., Khanal, S., Gutierrez, P., Teegerstrom, T., Zuniga Vazquez, D., Fan, N., & Quinn, J. (2021). Economic and environmental analyses of incorporating guar into the American southwest. *Agricultural Systems*, 191, 103146. doi:10.1016/j.agsy.2021.103146

Module I - Facility Location and Transportation

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SBAR research Input

Equivalent GHG emissions

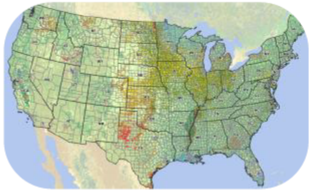
Economic costs
- Capital construction
- Harvesting & hauling
- Loading & unloading
- Processing
- Transp. & distr.

Emissions
- Constructions
- Transportation
- Processing
- Distribution

Social Impact
- Local accrued jobs
- Earning per work hour

Biomass
- Yield
- Conversion factor

CropScape Input
- Crops' acreage
- Crops' location



GIS Layers Inputs
- Irrigation districts
- Groundwater conservations districts
- Medium and high development
- Railroad
- Highway and primary roads

Stochastic and Multi-objective Optimization Model
C++ and CPLEX

ArcGIS Pro 2.4.0
- Defines farm groups
- Identify potential facility locations

MILO Benders Decomposition

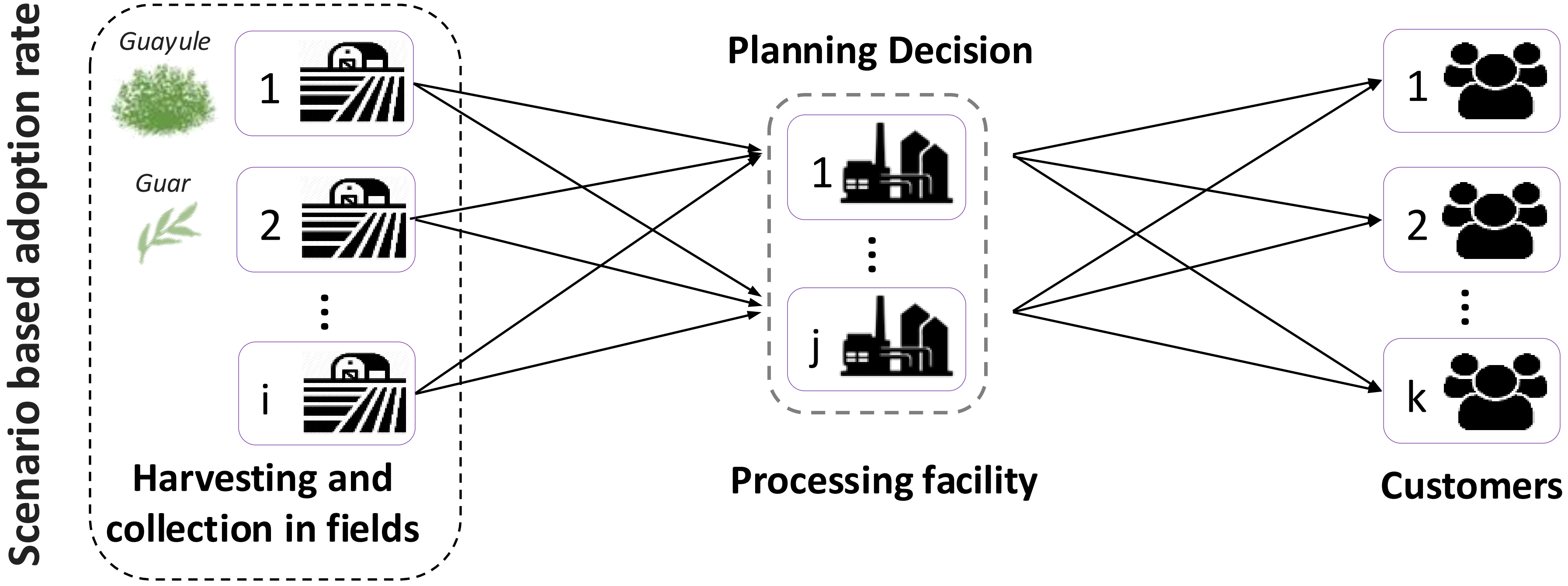
Origin-destination cost matrix
- Optimized route (distance)from farm groups to facility location candidates

Optimal Solution
Optimal facility location
Expected productivity from farm groups

Optimal Design of Guayule and Guar Supply Chains

Stochastic mixed-integer linear optimization modeling

- ✓ **Economic objective**: to **minimize** the capital cost and the annual operation cost.
- ✓ **Environmental objective**: **minimize** the total CO2-equivalent GHG emissions.
- ✓ **Social objective**: **maximize** the accrued local jobs.



Software and Tools

ArcGIS

CropScape

IBM CPLEX

Optimization Model of Module I - Objective Function

Multi-Objective:

$$\min_{x,cap,u,v} \underbrace{\theta^1 EcoBen}_{\text{Economical}} + \underbrace{\theta^2 EnvImp}_{\text{Environmental}} + \underbrace{\max \theta^3 SocImp}_{\text{Social}}$$

Economic objective:

Minimize the total cost, including the total **capital** and **operation costs**.

Environmental objective:

Minimize the total CO2-equivalent greenhouse gas (GHG) emission cost resulting from the operations of the biomass supply chain.

Social objective:

Maximize the accrued local jobs, including the jobs created during the construction phase of processing facilities and the operation of the supply chain.

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Optimization Model of Module I - Objective Function

$$\min_{x,cap,u,v} \underbrace{\theta^1 EcoBen}_{\text{Economical}} + \underbrace{\theta^2 EnvImp}_{\text{Environmental}} + \underbrace{\max \theta^3 SocImp}_{\text{Social}}$$

Economical

Expected cost

$$EcoBen = \underbrace{\sum_{b \in \mathscr{B}} C_b^{cap} x_b}_{\text{Processing facility capital cost}} + \boxed{\sum_{\omega \in \Omega} Prob(\omega)} \left(O^{HCost}(\omega) + O^{T\&PCost}(\omega) + O^{DCost}(\omega) \right)$$

$$O^{HCost}(\omega) = (C^H + C^L) \sum_{f \in \mathscr{F}} \sum_{b \in \mathscr{B}} u_{fb}^{(\omega)}$$

Harvesting cost

$$O^{T\&PCost}(\omega) = \sum_{f \in \mathscr{F}} \sum_{b \in \mathscr{B}} \left(C^T L_{fb} + C^P \right) u_{fb}^{(\omega)}$$

Transportation and processing cost

$$O^{DCost}(\omega) = \sum_{b \in \mathscr{B}} \sum_{p \in \mathscr{P}} \sum_{c \in \mathscr{C}} C_p^D v_{pbc}^{(\omega)}$$

Distribution cost

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Optimization Model of Module I - Objective Function

Environmental

$$EnvImp = \underbrace{\varepsilon \sum_{b\in\mathscr{B}} \mu_b x_b}_{\text{Processing facility Construction emissions}} + \overbrace{\boxed{\sum_{\omega\in\Omega} Prob(\omega)}}^{\text{Expected impact}} \Bigg(\underbrace{\varepsilon \sum_{f\in\mathscr{F}} \sum_{b\in\mathscr{B}} L_{fb} u_{fb}^{(\omega)} \beta}_{\text{Transportation emissions}} + \varepsilon \sum_{b\in\mathscr{B}} \sum_{p\in\mathscr{P}} \sum_{c\in\mathscr{C}} \underbrace{(L_{bc}\gamma_p + \delta_p) v_{pbc}^{(\omega)}}_{\text{Processing and distribution emissions}} \Bigg)$$

Social

$$SocImp = \underbrace{\sum_{b\in\mathscr{B}} (E_b^B H^B) x_b}_{\text{Social benefit from Processing facility construction jobs}} + \overbrace{\boxed{\sum_{\omega\in\Omega} Prob(\omega)}}^{\text{Expected benefit}} \Bigg(\sum_{f\in\mathscr{F}} \sum_{b\in\mathscr{B}} \underbrace{(E_f^H H^H + E_f^T H^T L_{fb}) u_{fb}^{(\omega)}}_{\text{Social benefit from transportation jobs}} + \sum_{b\in\mathscr{B}} \sum_{p\in\mathscr{P}} \sum_{c\in\mathscr{C}} \underbrace{(E_b^P H_b^P + E_b^D H_b^D L_{bc}) v_{pbc}^{(\omega)}}_{\text{Social benefit from processing and distribution jobs}} \Bigg)$$

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Optimization Model of Module I - Constraints

Number of processing facilities and their capacity

No. facilities $\sum_{b\in\mathscr{B}} x_b \le K$

Capacity $Min_b x_b \le cap_b \le Max_b x_b, \ \forall b$

Transportation, distribution, and demand requirements

Transportation $\sum_{f\in\mathscr{F}} u_{fb}^{(\omega)} = cap_b, \ \forall b, \forall \omega$

Distribution $cap_b \theta_p = \sum_{c\in\mathscr{C}} v_{pbc}^{(\omega)}, \ \forall p, \forall b, \forall \omega$

Transportation and distribution availability

$u_{fb}^{(\omega)} \le Max_b x_b, \ \forall f, \forall b, \forall \omega$

$\sum_{p\in\mathscr{P}} \sum_{c\in\mathscr{C}} v_{pbc}^{(\omega)} \le Max_b x_b, \ \forall b, \forall \omega$

Demand $\sum_{b\in\mathscr{B}} v_{pbc}^{(\omega)} \ge D_{pc}, \ \forall p, \forall c, \forall \omega$

Harvesting capacity and water availability

Harvesting capacity $\sum_{b\in\mathscr{B}} u_{fb}^{(\omega)} \le P_f^{(\omega)}, \ \forall f, \forall \omega$

Irrigation district water availability $\sum_{f\in\mathscr{F}^i} \sum_{b\in\mathscr{B}} u_{fb}^{(\omega)} U_f \le W_i, \ \forall i, \forall \omega$

Environmental and social bounds

Environmental impact upper bound $EnvImp \le UB^{EnvImp}$

Social benefit lower bound $SocImp \ge LB^{SocImp}$

Binary and nonnegativity limitations

Binary $x_b \in \{1,0\}, \ \forall b$

Nonnegativity $cap_b, u_{fb}^{(\omega)}, v_{pbc}^{(\omega)} \ge 0, \ \forall f, \forall b, \forall p, \forall c,$

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Data Inputs - Farm/Field Locations

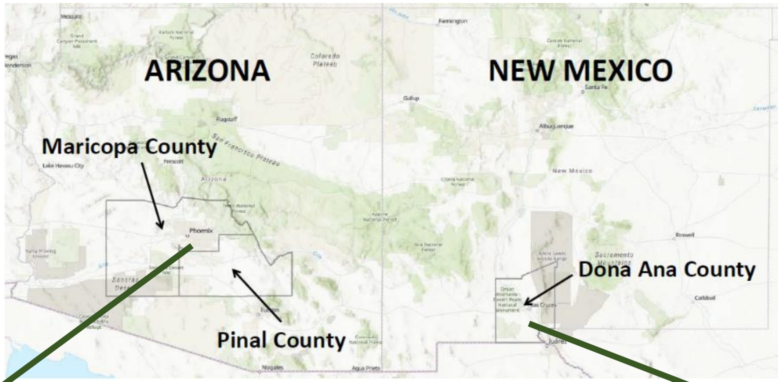
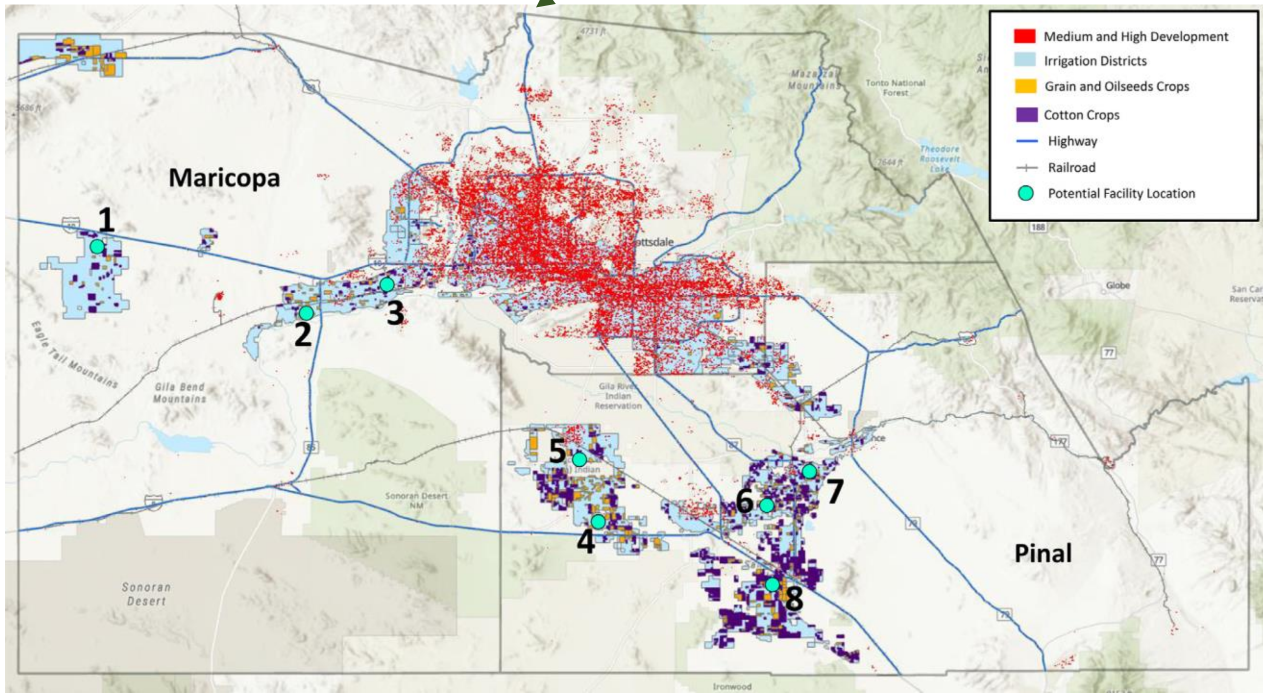


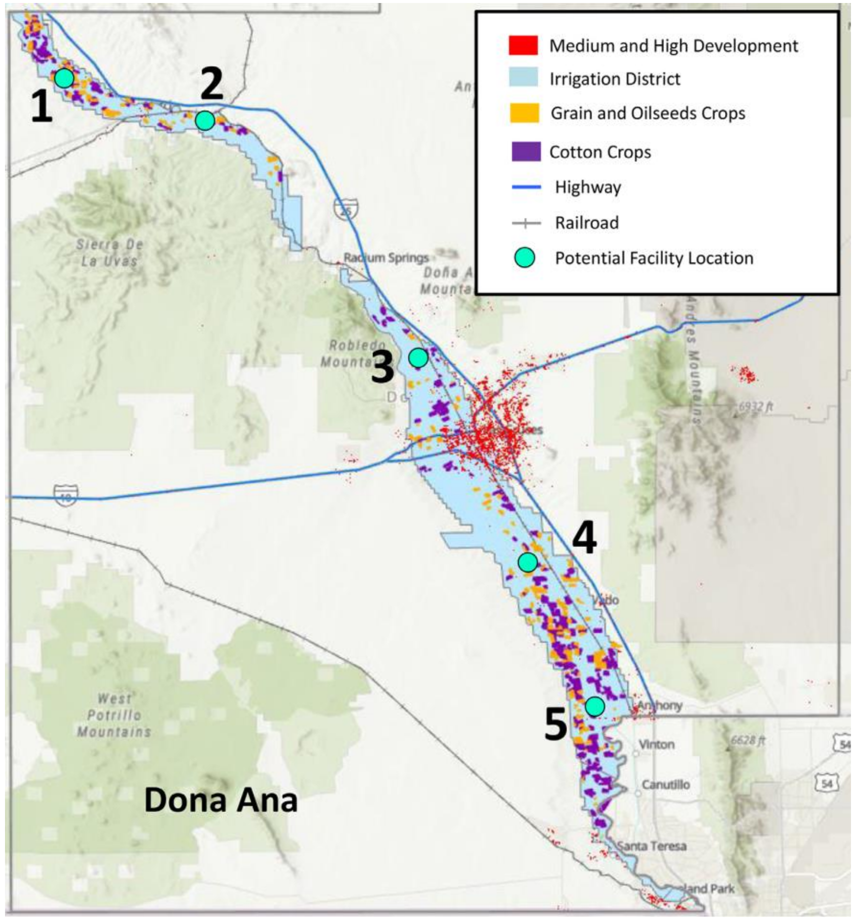
Fig. 1: Case study counties' locations

Guayule

Guar



Maricopa and Pinal's GIS information



Dona Ana's GIS information.

Data Inputs - Parameter Settings

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TABLE II: Adoption Rate Probabilities for Stochastic Scenarios and Crop Percentages

Adoption Rate Probability			0.15	0.33	0.27	0.08	0.07	0.01	0.03	0.04	0.01	0.00
Maricopa and Pinal	Guayule	% from all crops	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%
		% from CGO	35%	42%	49%	57%	64%	71%	78%	86%	93%	100%
Dona Ana	Guar	% from all crops	14.3%	14.9%	15.6%	16.3%	17.0%	17.7%	18.3%	19.0%	19.7%	20.4%
		% from CGO	70%	73%	77%	80%	83%	87%	90%	93%	97%	100%

TABLE III: Costs and Capacity Inputs

Concept	Unit	Guayule	Guar
Farm yield	t/acre	12	0.154
Processing facility's capital cost	MMUSD	266	4
Processing facility's maximum capacity	t/year	499,500	13,453
Processing facility's minimum capacity	t/year	405,000	

TABLE V: Maricopa and Pinal's Irrigation Districts

1	Adaman No.36	7	Hohokam	13	Roosevelt Water Conservation
2	Aguila	8	Maricopa Stanfield	14	Saint Johns
3	Arlington Canal Company	9	Maricopa Water District	15	Salt River Valley Water Users Association
4	Buckeye	10	New Magma	16	San Carlos
5	Central Arizona	11	Queen Creek	17	Tonopah
6	Harquahala Valley	12	Roosevelt		

TABLE VII: Customers' Demands

Customer No.	Products	Demand (t)			
		Rubber	Resin	Endosperm	Husk and germ
1	Agricultural Machinery Tires	5000	5000	-	-
2	Tubes and Flaps	5000	5000	-	-
3	Off-the-road Tires	5000	5000	-	-
4	Tires	5000	5000	-	-
5	Retreading Materials	3000	3000	-	-
6	Retreading Equipment	3000	3000	-	-
7	Guar gum and Guar meal	-	-	200	200
8		-	-	200	200
9		-	-	100	100
10		-	-	100	100

TABLE IV: Adjusted Earning Per Work Hour

Earning per work hour for	Unit	Maricopa	Pinal	Dona Ana
Construction	USD/hr	30.9	24.8	18.48
Harvesting	USD/hr	21.3	10.6	11.4
Transportation	USD/hr	22	15.4	14.6
Production	USD/hr	36.3	16.3	15.59

Optimal Solution

United States Department of Agriculture
National Institute of Food and Agriculture

TABLE VIII: Results Summary Breakdown (MMUSD)

Concept	Maricopa and Pinal	Dona Ana
Capital cost	266.63	3.97
Harvesting/hauling cost	19.40	0.86
Transportation and Processing cost	121.6	2.7
Distribution cost	2.98	0.13
Economic objective	410.6	6.8
Environmental objective	19.2	0.2
Social objective	12.1	0.1
Total objective	441.9	7.1

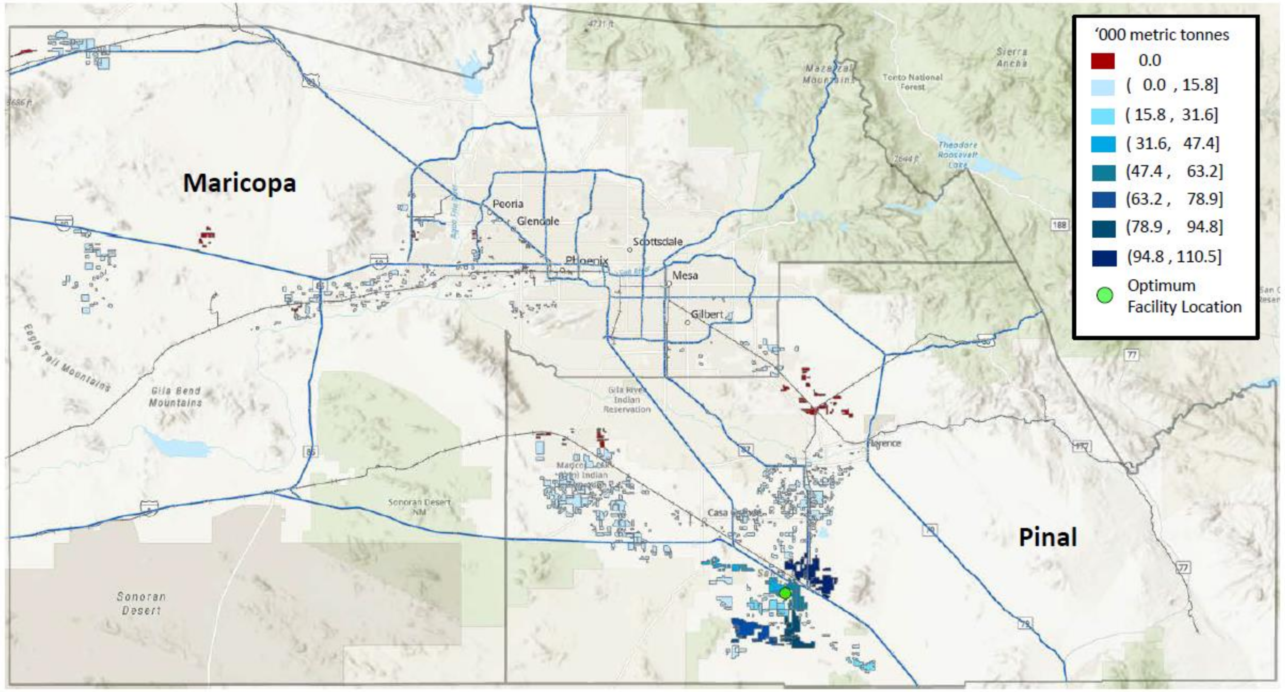


Fig. 4: Expected guayule productivity from Maricopa and Pinal counties' CGO farms

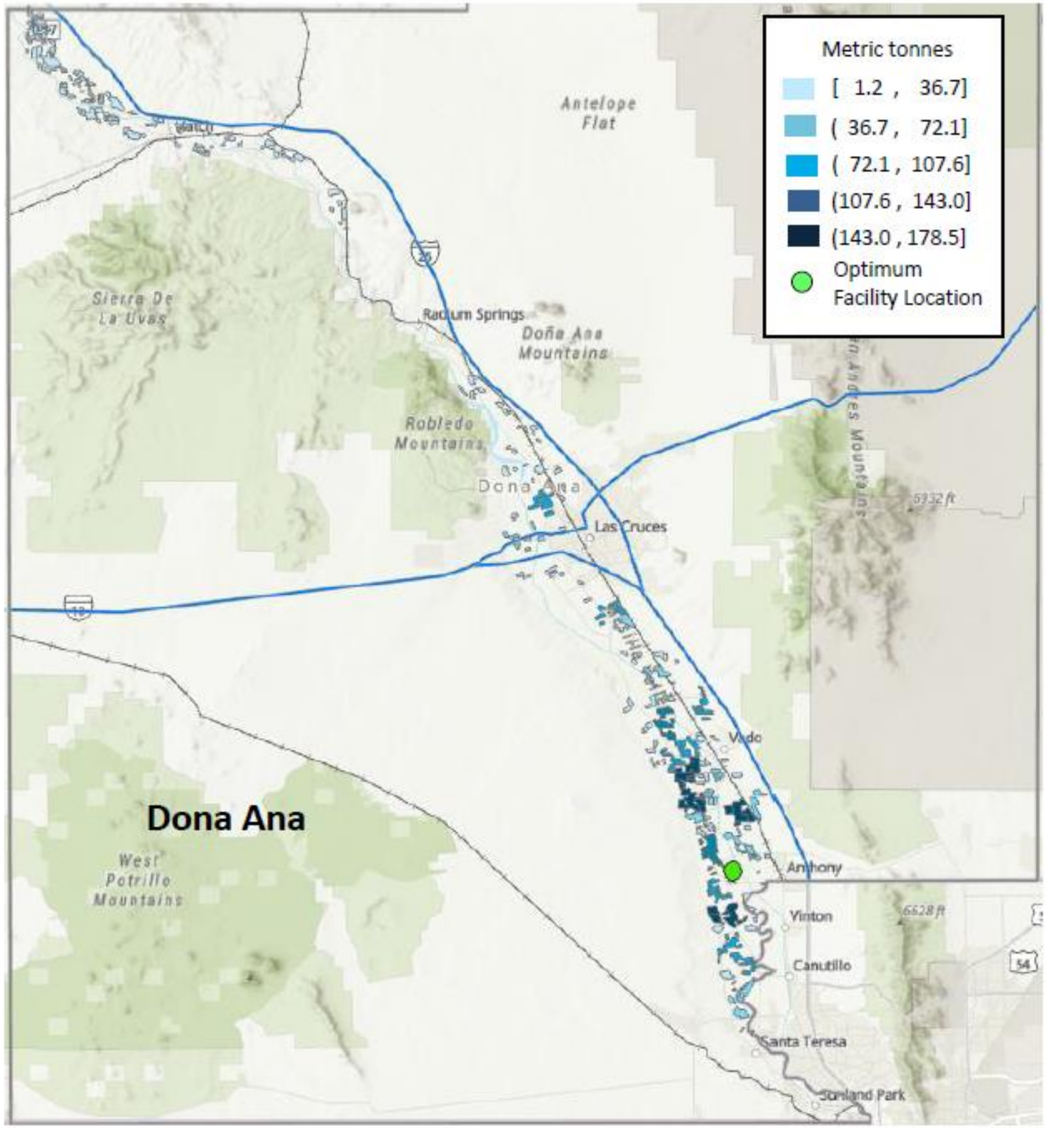
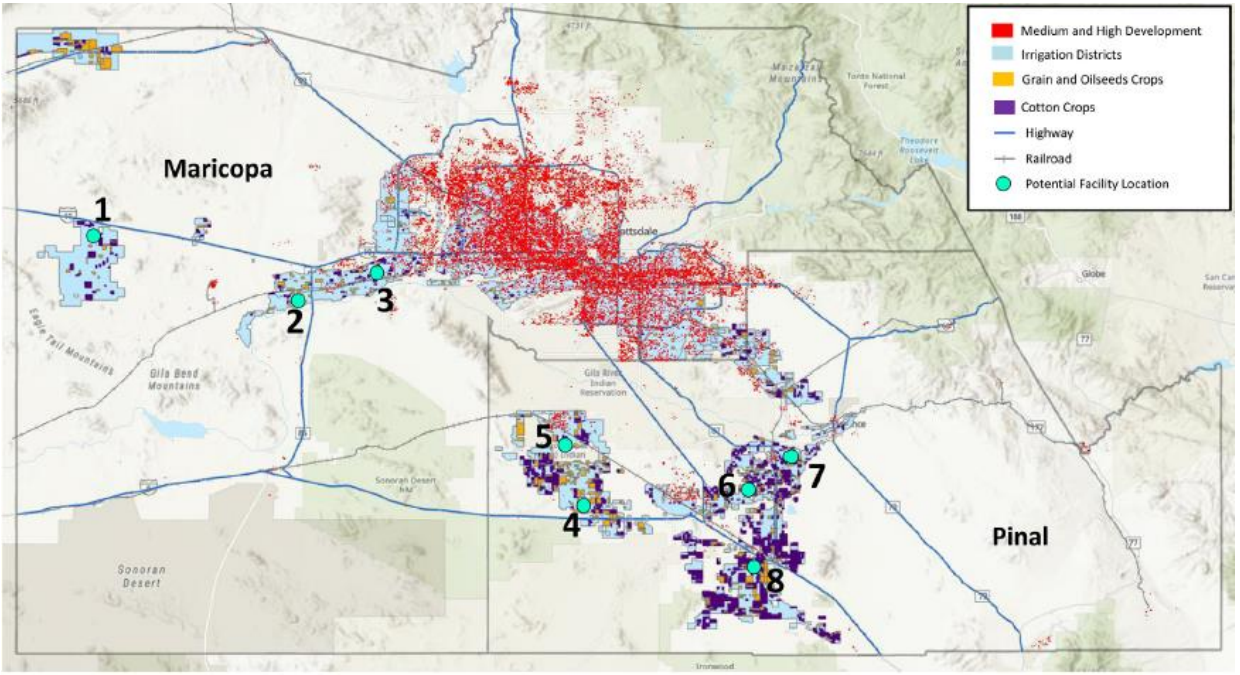
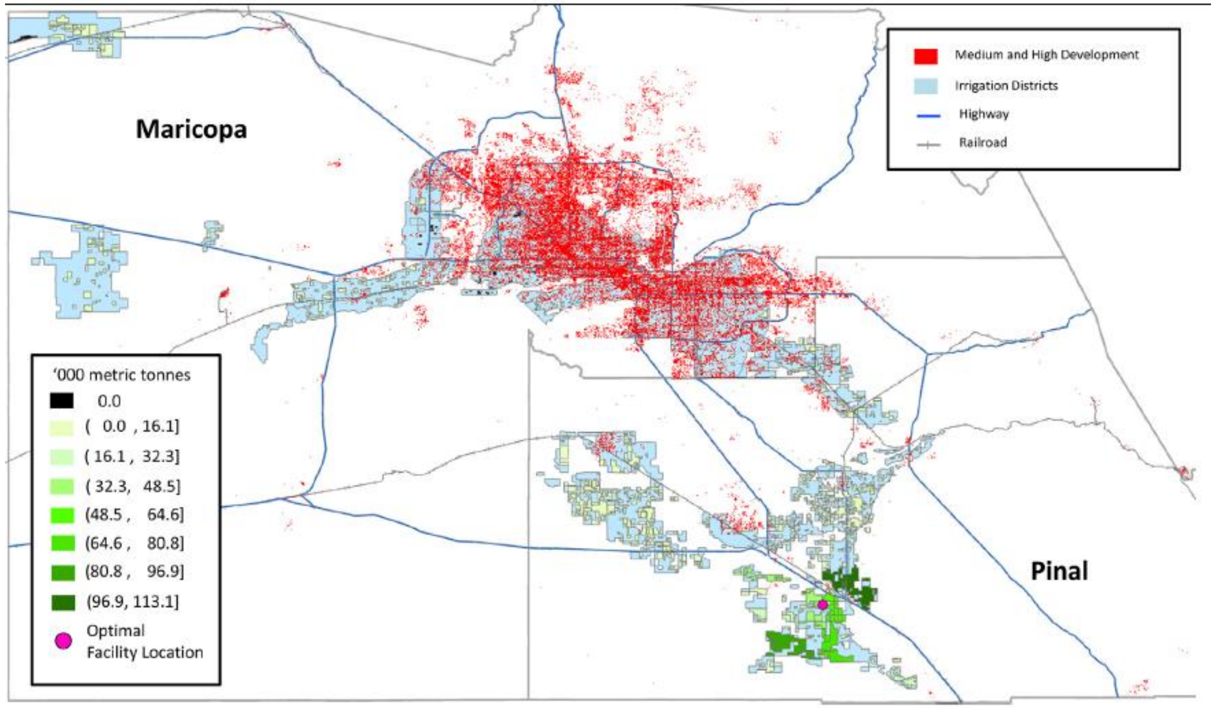


Fig. 5: Expected guar productivity from Dona Ana county's CGO farms

Optimal Facility Location for Guayule



Maricopa and Pinal's GIS information



Expected guayule productivity from Maricopa and Pinal counties' CGO farms

Optimal Facility Location for Guar

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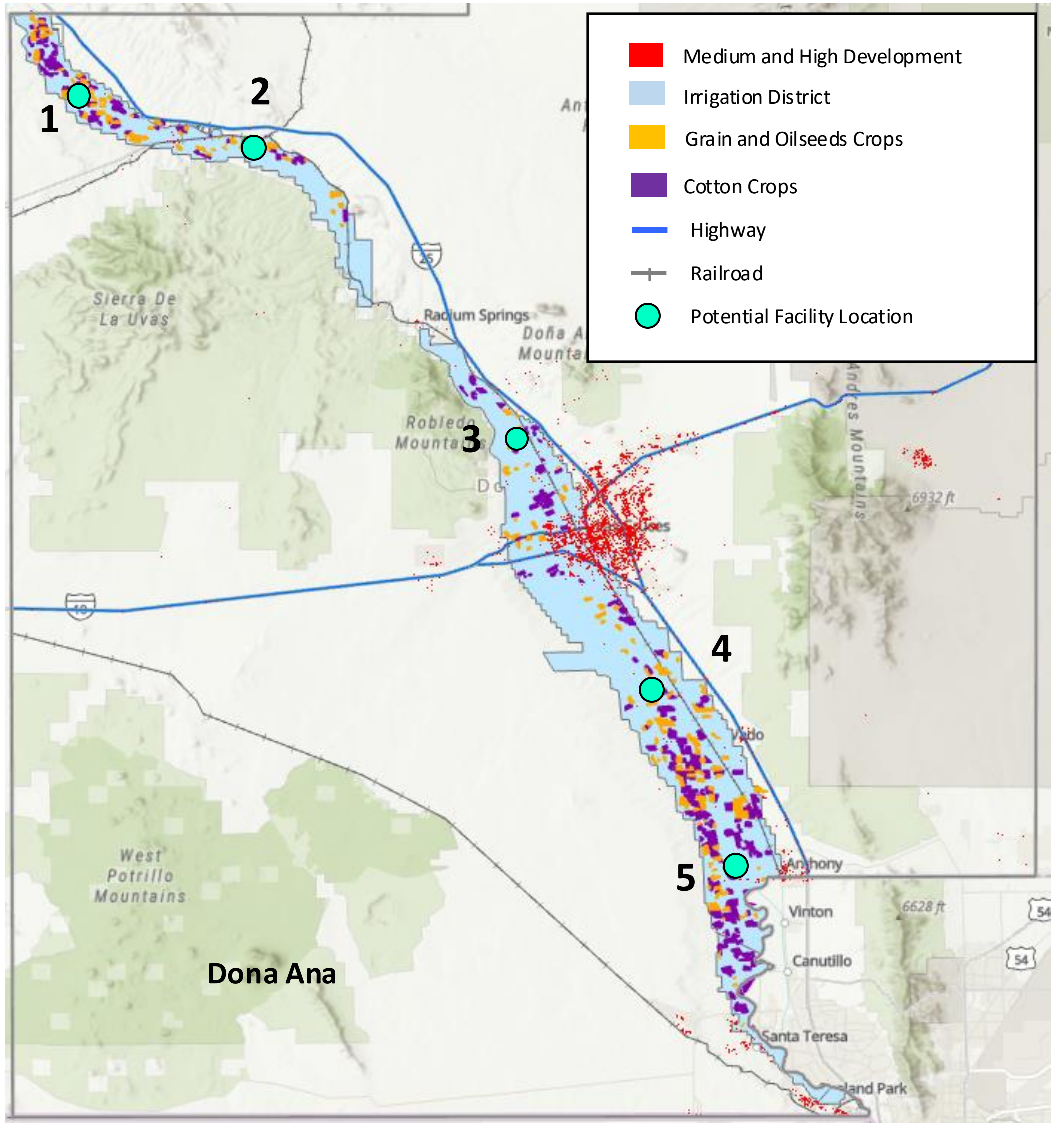
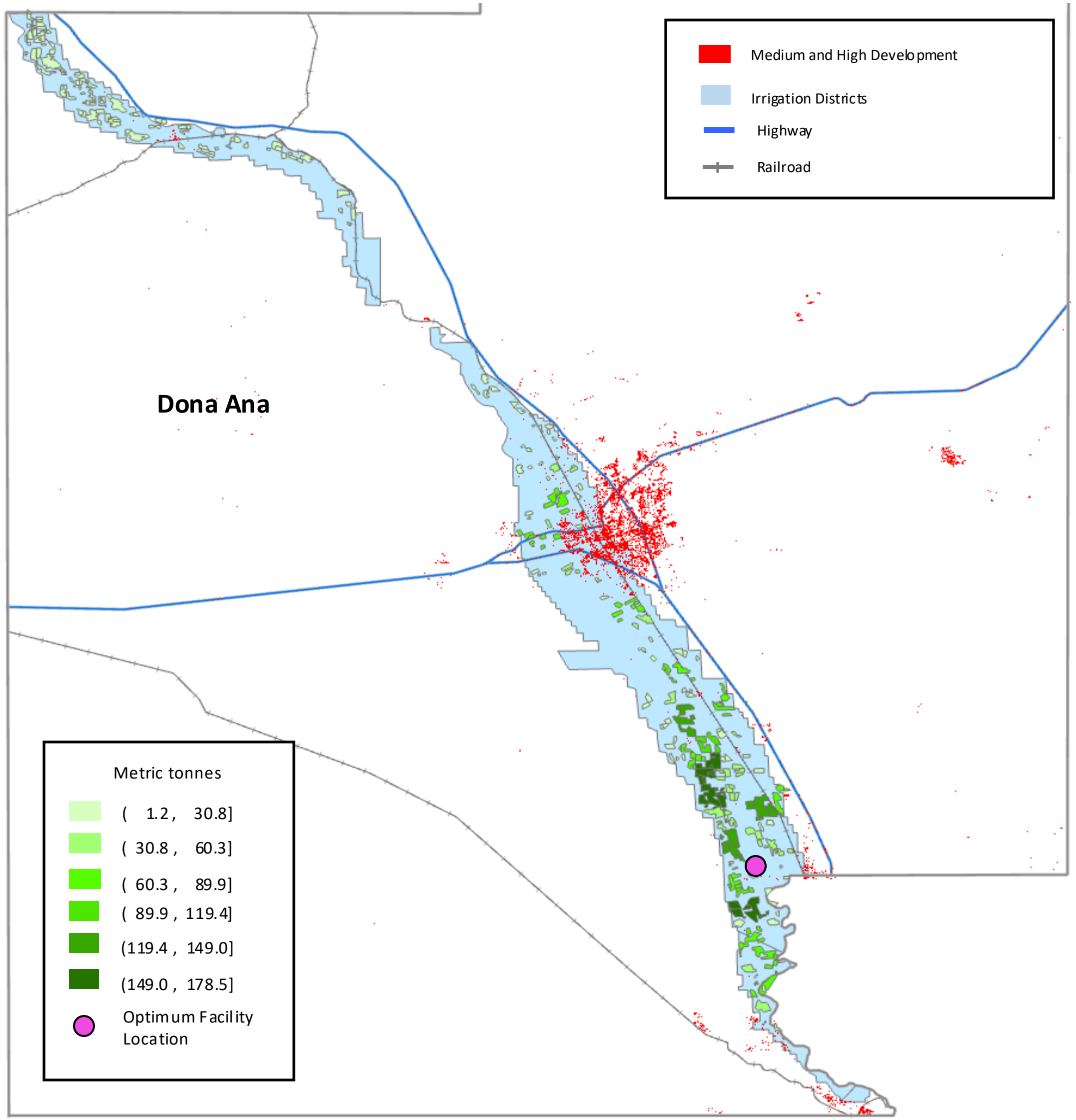


Dona Ana's GIS information



Expected guar productivity from Dona Ana County's CGO farms

Sensitivity Analysis

TABLE IX: Sensitivity Analisys for Weighted Factors

Weighted factor	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
θ^1	-	0.50	0.8	0.25	0.1	0.25	0.1
θ^2	-	0.25	0.1	0.50	0.8	0.25	0.1
θ^3	-	0.25	0.1	0.25	0.1	0.50	0.8

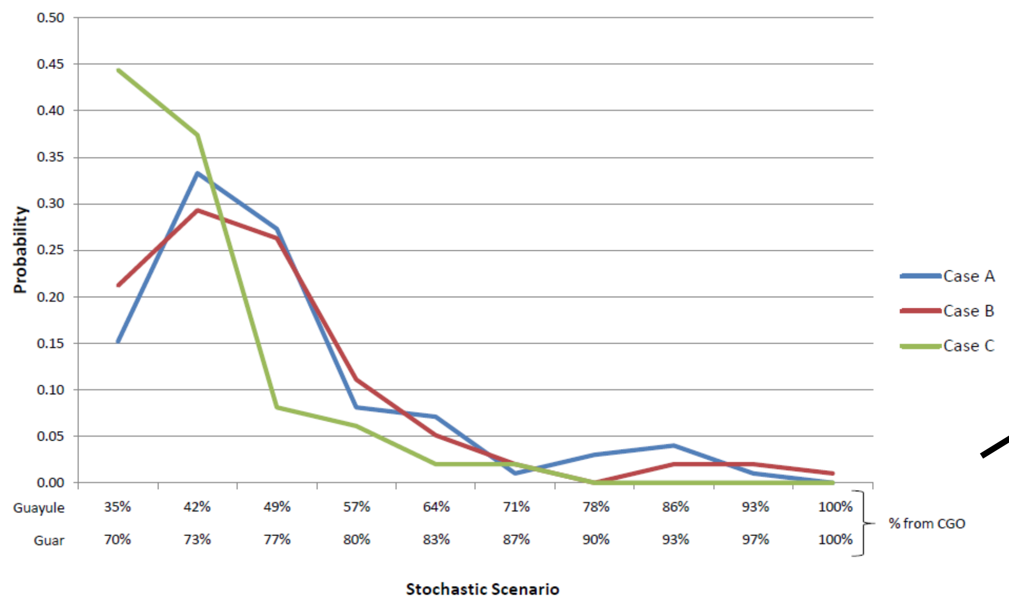


Fig. 6: Sensitivity analysis for adoption rate probabilities

TABLE X: Sensitivity Analysis Results

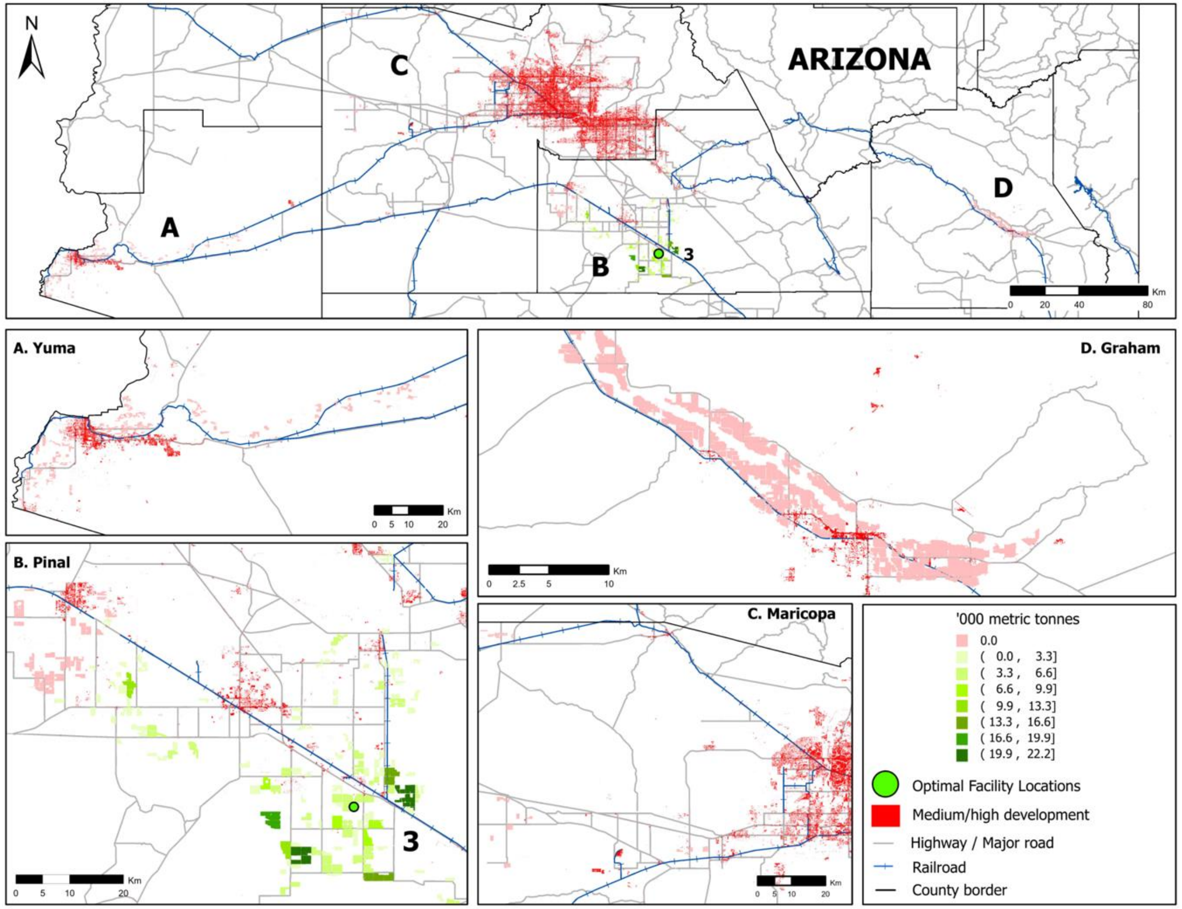
Concept		Maricopa and Pinal							Dona Ana						
Case		1	2	3	4	5	6	7	1	2	3	4	5	6	7
θ^1		-	0.50	0.8	0.25	0.1	0.25	0.1	-	0.50	0.8	0.25	0.1	0.25	0.1
θ^2		-	0.25	0.1	0.50	0.8	0.25	0.1	-	0.25	0.1	0.50	0.8	0.25	0.1
θ^3		-	0.25	0.1	0.25	0.1	0.50	0.8	-	0.25	0.1	0.25	0.1	0.50	0.8
A	T&P Cost*:	121.6	121.6	125.8	127.3	121.6	121.6	127.3	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Economic Objective:	410.6	205.3	331.8	104.1	41.1	102.6	41.6	6.8	3.4	5.5	1.7	0.7	1.7	0.7
	Environmental Objective:	19.2	4.8	1.9	9.7	15.4	4.8	1.9	0.2	0.0	0.0	0.1	0.1	0.0	0.0
	Social Objective:	12.1	4.8	1.6	3.2	1.3	6.0	10.4	0.1	0.2	0.0	0.0	0.0	0.0	0.1
	Total Objective:	441.9	214.9	335.4	117.1	57.8	113.5	54.0	7.1	3.7	5.5	1.8	0.9	1.8	0.8
	Location:	8	8	8	3	3	8	8	5	5	5	5	5	5	5
B	T&P Cost*:	128.6	127.7	127.1	122.8	128.6	122.8	128.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Economic Objective:	417.8	208.5	333.1	103.0	41.8	103.0	41.8	6.8	3.4	5.5	1.7	0.7	1.7	0.7
	Environmental Objective:	19.6	4.9	1.9	9.7	15.6	4.8	2.0	0.2	0.0	0.0	0.1	0.1	0.0	0.0
	Social Objective:	13.1	3.7	1.6	3.1	1.3	6.1	10.5	0.1	0.0	0.0	0.0	0.0	0.0	0.1
	Total Objective:	450.5	217.0	336.7	115.7	58.7	113.9	54.2	7.1	3.5	5.5	1.8	0.8	1.8	0.8
	Location:	3	3	8	3	3	3	8	5	5	5	4	4	4	5
C	T&P Cost*:	128.7	123.0	127.4	123.0	128.7	128.7	128.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Economic Objective:	417.9	206.1	333.3	103.1	41.8	104.5	41.8	6.9	3.4	5.5	1.7	0.7	1.7	0.7
	Environmental Objective:	19.6	4.8	2.0	9.7	15.6	4.9	2.0	0.2	0.0	0.0	0.1	0.1	0.0	0.0
	Social Objective:	13.1	3.1	1.6	3.1	1.3	6.6	10.5	0.1	0.0	0.0	0.0	0.0	0.0	0.1
	Total Objective:	450.5	214.0	336.8	115.8	58.7	115.9	54.2	7.1	3.5	5.5	1.8	0.8	1.8	0.8
	Location:	8	8	3	8	8	3	3	4	5	5	4	5	4	4

*Transportation and processing cost

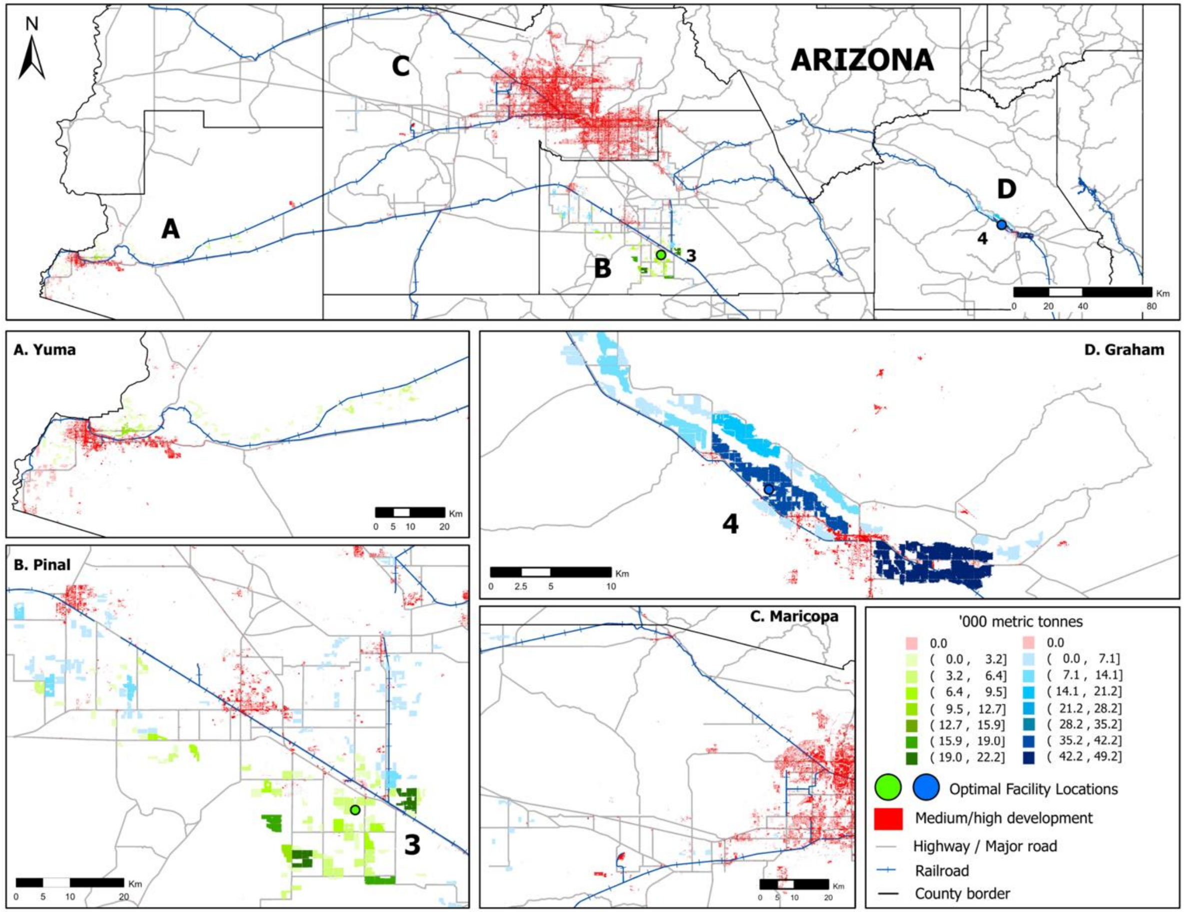
United States Department of Agriculture

National Institute of Food and Agriculture

Sensitivity Analysis for Guayule



(a) 1 optimal processing facility location



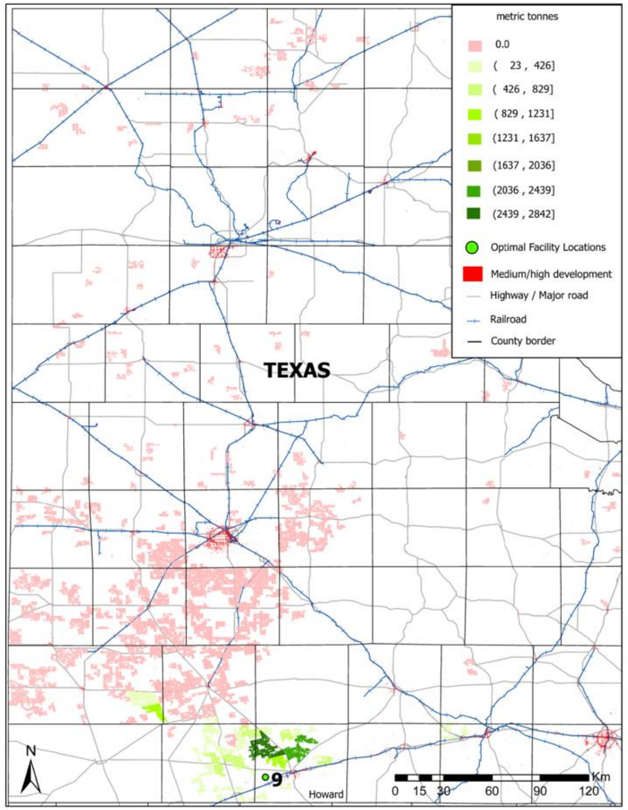
(a) 2 optimal processing facility locations

Sensitivity analysis for the processing facility location and expected guayule productivity in Arizona.

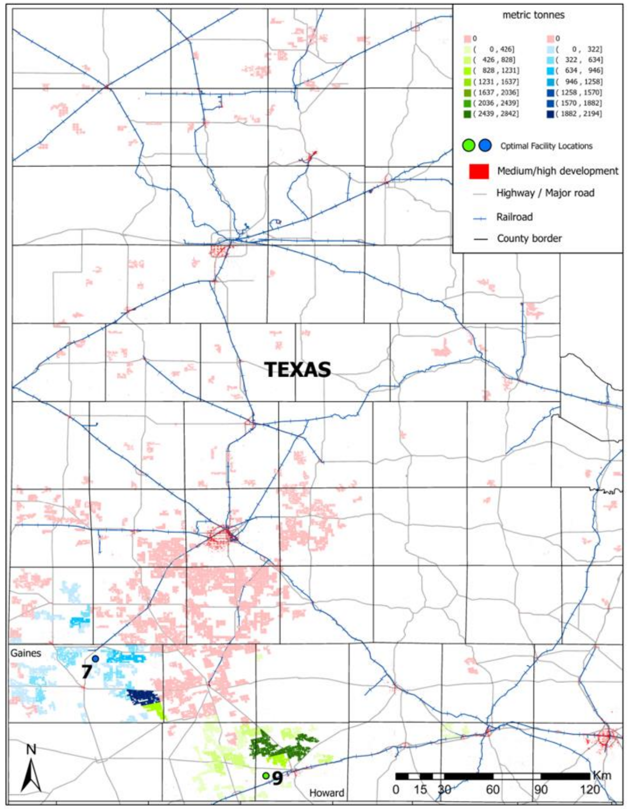
Sensitivity Analysis for Guar

United States Department of Agriculture

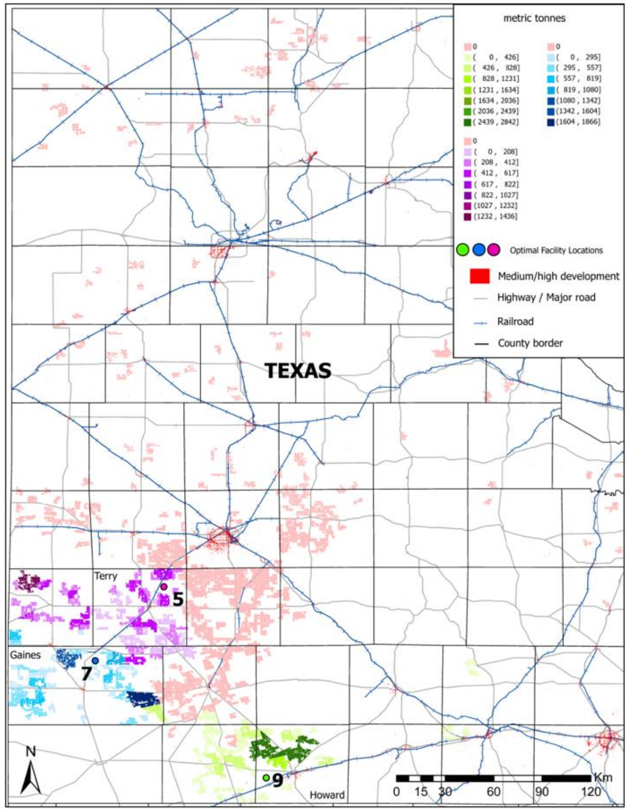
National Institute of Food and Agriculture



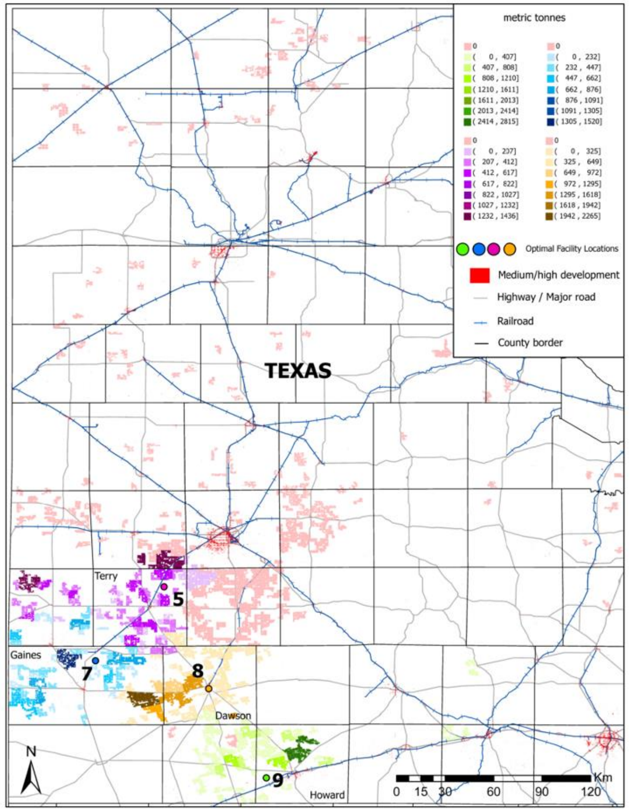
(a) 1 optimal processing facility location



(b) 2 optimal processing facility locations



(c) 3 optimal processing facility locations



(d) 4 optimal processing facility locations

Sensitivity analysis for processing facility location and expected guar productivity in Northwestern Texas

Biomass Supply Chains for Guayule and Guar

SBAR

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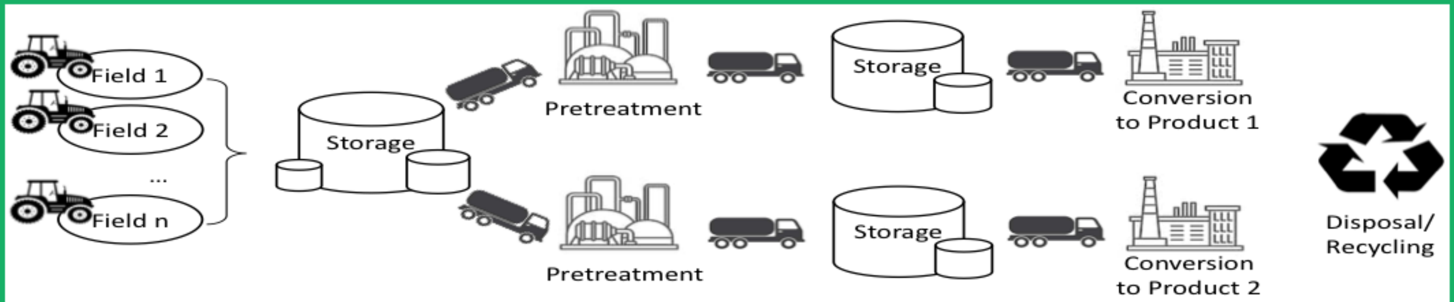
Biomass Supply Chains for Guar and Guayule

Physical Level



Decision Support Modules

Smart Farm Production and Scheduling
- Farm Production Planning
- Equipment Scheduling
- Harvest Scheduling

Smart Facility Planning and Transportation
- Facility Location
- Capacity Planning
- Shipment Scheduling
- Transportation Mode Choice and Routing

Smart Sustainability and Economics Analysis
- Regional Economics
- Social Impacts

Model and Algorithm Library

Optimization: stochastic programming and robust optimization

Statistical Machine Learning: supply and demand forecasting

LCA: life cycle assessment

Data and Information

Stakeholders: Bridgestone, farmers, end customers; third party logistics; local utility suppliers; government and policy makers; USDA

GIS (Geographic information system): Google map, NRCS@USDA

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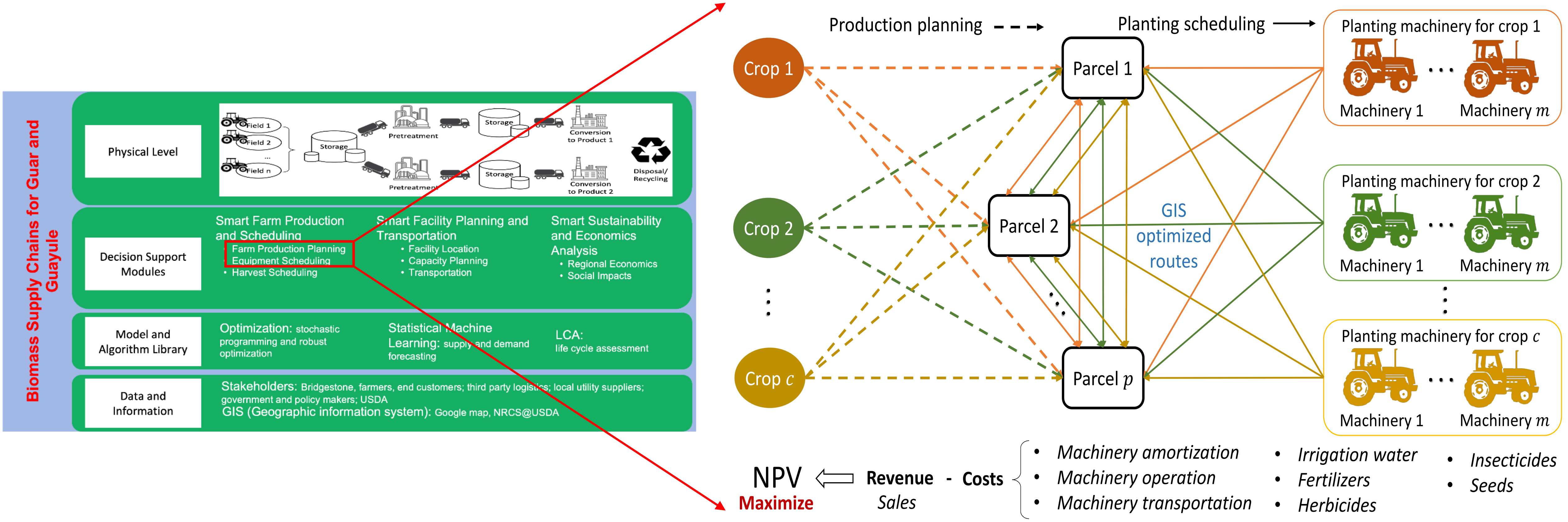
Module II - Smart Farm Production Plan and Scheduling Design

Guayule and Guar

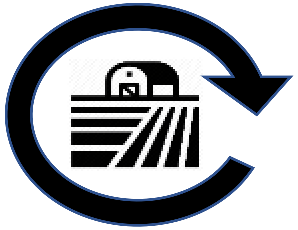


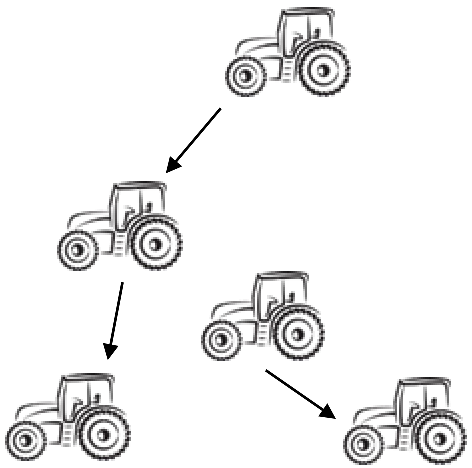
- D. A. Zuniga Vazquez, N. Fan, T. Teegerstrom, C. Seavert, H.M. Summers, E. Sproul, and J.C. Quinn (2021). Optimal Production Planning and Machinery Scheduling for Semi-Arid Farms, *Computers and Electronics in Agriculture*, 187, 106288. doi: 10.1016/j.compag.2021.106288

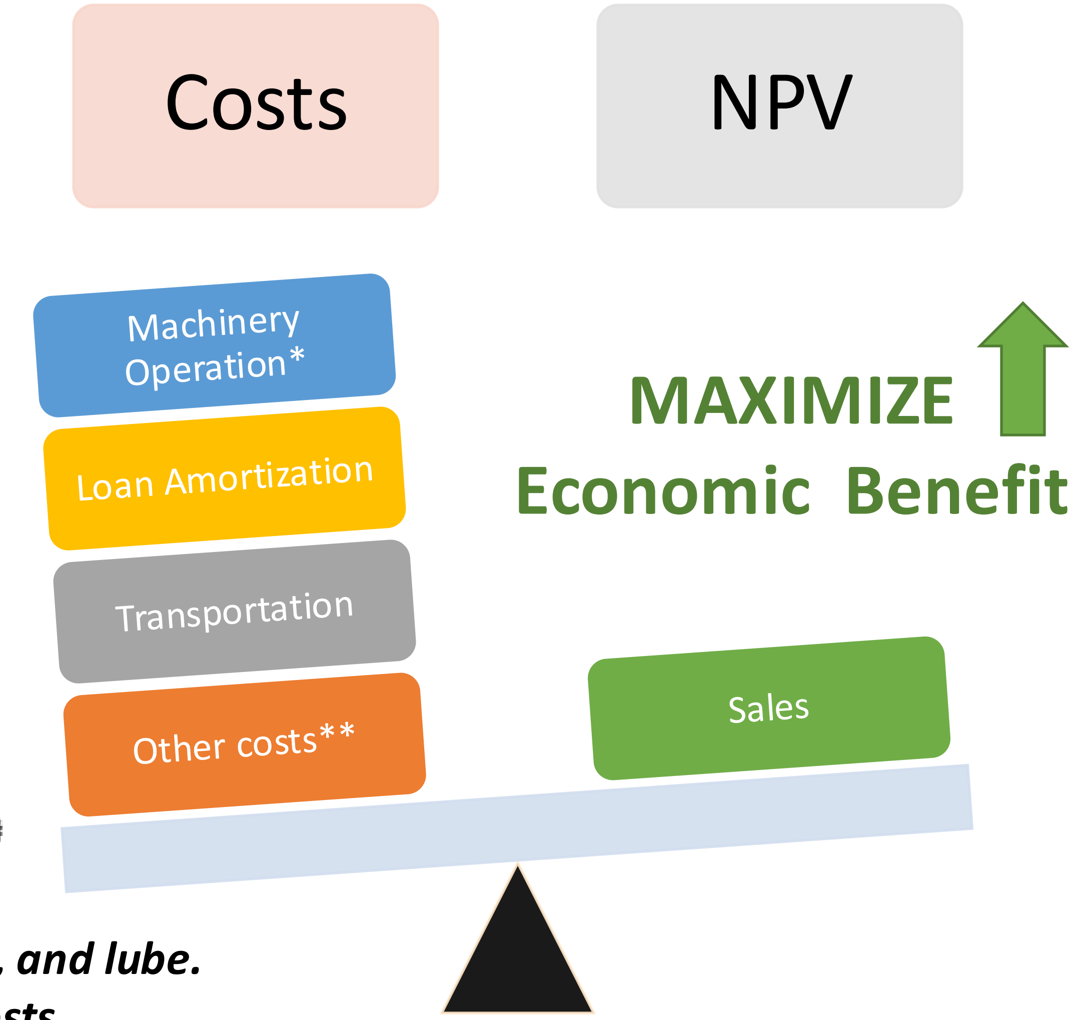
Module II - Smart Farm Production Plan and Scheduling Design

Guayule and Guar

- Model constraints
  - Crop rotation
  - Multi-machinery scheduling
- Input parameters
  - Crop parameters
  - Machinery limits
- Case Studies
  - Guar in Texas
  - Guayule in Pinal County, AZ







**Machinery operation includes labor, repairs, maintenance, fuel, and lube.*
***Other costs includes water, seeds, fertilizers, and herbicides costs.*

Module II - Smart Farm Production Plan and Scheduling Design

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Large-scale ILO model

SBAR Research Input

Revenue
- Productivity
- Sale price

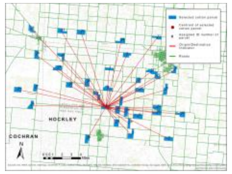
Cost
- Loan amortization
- Operation
- Transportation
- Others

Minimum Demand

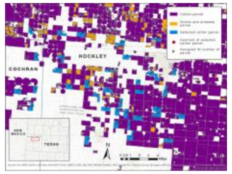
Distance between fields

Number of planting machinery, fields, time periods

CropScape Input

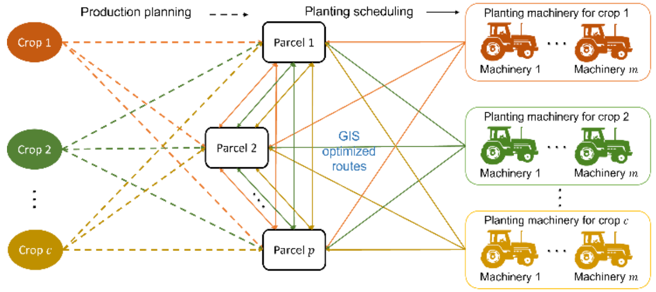


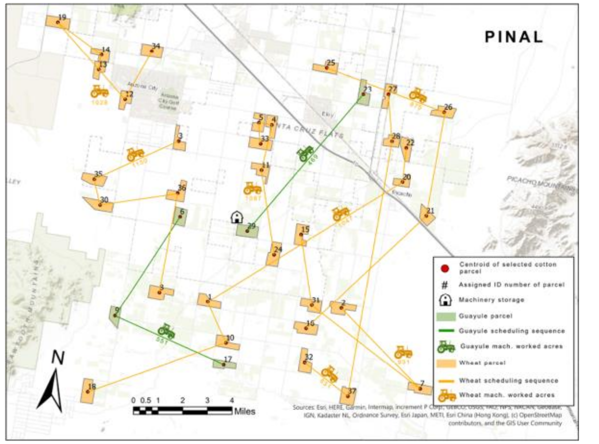
- Crop's acreage
- Crop's location



GIS Layers Input

- Irrigation districts
- Groundwater conservation
- Medium and high development
- Railroad
- Highway and primary roads





C++ & CPLEX 12.7

ArcGIS Pro 2.4.0

Case study
- *Guayule*
- *Guar*

Optimal Solution

- A production plan maximizing the farmers' net present value (NPV)
- Optimal Planting scheduling for different crops

Production Planning and Machinery Scheduling for Guar and Guayule

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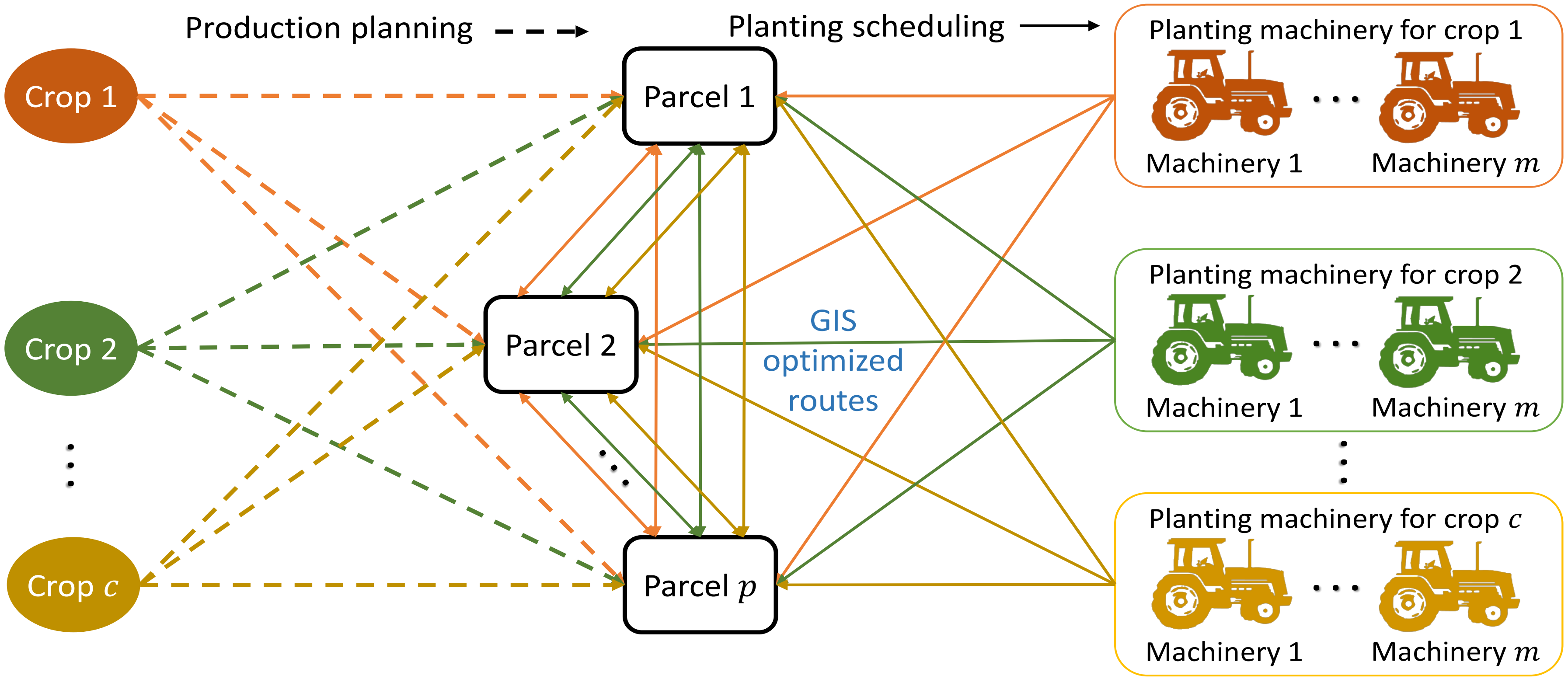
Main Goals

- Determine which fields to adopt guar and guayule
- Equipment scheduling for farm operations



Such that the farmers' profits is maximized

NPV **Maximize** ⟸ **Revenue** *Sales* - **Costs**

- *Machinery amortization*
- *Machinery operation*
- *Machinery transportation*
- *Irrigation water*
- *Fertilizers*
- *Herbicides*
- *Insecticides*
- *Seeds*

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Optimization Model of Module II - Objective Function

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Maximize the Net Present Value

$$\max_{\substack{\boldsymbol{x},\boldsymbol{y},\boldsymbol{z},\\ \boldsymbol{s},\boldsymbol{u},\boldsymbol{v},\boldsymbol{w}}} \sum_{t\in\mathcal{T}} \frac{1}{(1+\alpha)^{t-1}}(Rev_t - TC_t)$$

Farmers' Revenues

$$Rev_t = \sum_{c\in\mathcal{C}}\sum_{p\in\mathcal{P}} x^t_{cp}(P_{cp}S_c)(1+IR^{Inc})^t$$

***t*: time frame different for guar and guayule**

Costs:

- Seed costs
- Fertilizers
- Herbicides
- Water
- Machinery
- Labor
- Machinery transportation

$$TC_t = LoanMach + MachOp + MachTrans + OtherCosts$$

$$LoanMach = \sum_{c\in\mathcal{C}}\left(\sum_{m\in\mathcal{M}^{\mathcal{P}}} C_c^{CapPM,t}u_{mc} + \sum_{n\in\mathcal{M}^{\mathcal{H}}} C_c^{CapHM,t}v_{nc}\right)$$

$$MachOp = \sum_{c\in\mathcal{C}}\sum_{p\in\mathcal{P}} x^t_{cp}A_{cp}(C_c^{PM} + C_c^{HM})(1+IR^{Cost})^t$$

$$MachTrans = \sum_{d=(p,q)\in\mathcal{D}}\sum_{c\in\mathcal{C}}\left(C_c^{TH}D_d y^t_{(p,q)c} + C_c^{TP}D_d z^t_{(p,q)c}\right)(1+IR^{Cost})^t$$

$$OtCosts = \sum_{c\in\mathcal{C}}\sum_{p\in\mathcal{P}} x^t_{cp}\Big(SeedCost + F\&HCost + WatCost\Big)(1+IR^{Cost})^t$$

Optimization Model of Module II - Constraints

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Resource demands & time limitation

One crop per field

$$\sum_{c\in\mathcal{C}} x_{cp}^{t} = 1,\ \forall p\in\mathcal{P}, \forall t\in\mathcal{T}$$

Minimum demand

$$\sum_{p\in\mathcal{P}} P_{cp}x_{cp}^{t} \geq D_{c}^{t},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T}$$

Crop rotation

$$\sum_{t'=t}^{t+N_c^R T_c} x_{cp}^{t'} \leq N_c^R T_c,\ \forall c\in\mathcal{C}, \forall p\in\mathcal{P}, t=1,\ldots,T-(N_c^R T_c)$$

Length of harvest season

$$\begin{cases} T_c x_{cp}^{1} - \sum_{t=1}^{T_c} x_{cp}^{t} \leq 0,\ \forall c\in\mathcal{C}, \forall p\in\mathcal{P} \\ \sum_{t'=t}^{t+T_c-1} x_{cp}^{t'} \geq T_c(x_{cp}^{t} - x_{cp}^{t-1}),\ \forall c\in\mathcal{C}, \forall p\in\mathcal{P}, t=1,\ldots,T-T_c+1 \\ \sum_{t'=t}^{T}(x_{cp}^{t'} - (x_{cp}^{t} - x_{cp}^{t-1})) \geq 0,\ \forall c\in\mathcal{C}, \forall p\in\mathcal{P}, t=T-T_c+2,\ldots,T \end{cases}$$

Water requirements

$$\sum_{p\in\mathcal{P}^i}\sum_{c\in\mathcal{C}} A_{cp}W_c^t x_{cp}^{t} \leq W_i^I,\ \forall i\in\mathcal{I}, \forall t\in\mathcal{T}$$

$$A_{cp}W_c^t x_{cp}^{t} \leq W_{cp}^F,\ \forall p, \forall c\in\mathcal{C}, \forall t\in\mathcal{T}$$

Machinery storage requirements

Departs from machinery storage

$$\begin{cases} \sum_{q\in\mathcal{P}:(1,q)\in\mathcal{D}} y_{(1,q)c}^{t} = \sum_{m\in\mathcal{M}^\mathcal{P}} u_{mc},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T} \\ \sum_{q\in\mathcal{P}:(1,q)\in\mathcal{D}} z_{(1,q)c}^{t} = \sum_{n\in\mathcal{M}^\mathcal{H}} v_{nc},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T} \end{cases}$$

Returns to machinery storage

$$\begin{cases} \sum_{p\in\mathcal{P}:(p,1)\in\mathcal{D}} y_{(p,1)c}^{t} = \sum_{m\in\mathcal{M}^\mathcal{P}} u_{mc},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T} \\ \sum_{p\in\mathcal{P}:(p,1)\in\mathcal{D}} z_{(p,1)c}^{t} = \sum_{n\in\mathcal{M}^\mathcal{H}} v_{nc},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T} \end{cases}$$

Machinery capacity limitations

$$\frac{1}{M^{CapP}}\sum_{p\in\mathcal{P}} A_{cp}x_{cp}^{t} \leq \sum_{m\in\mathcal{M}^\mathcal{P}} u_{mc},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T}$$

$$\frac{1}{M^{CapH}}\sum_{p\in\mathcal{P}} A_{cp}x_{cp}^{t} \leq \sum_{n\in\mathcal{M}^\mathcal{H}} v_{nc},\ \forall c\in\mathcal{C}, \forall t\in\mathcal{T}$$

Optimization Model of Module II - Constraints

Machinery scheduling requirements

One machinery enters per parcel

$$\sum_{q \in \mathcal{P}:(q,p) \in \mathcal{D}} y^t_{(q,p)c} = x^t_{cp}, \quad \forall c \in \mathcal{C}, \forall p \geq 2, p \neq q \in \mathcal{P}, \forall t \in \mathcal{T}$$

$$\sum_{q \in \mathcal{P}:(q,p) \in \mathcal{D}} z^t_{(q,p)c} = x^t_{cp}, \quad \forall c \in \mathcal{C}, \forall p \geq 2, p \neq q \in \mathcal{P}, \forall t \in \mathcal{T}$$

One machinery leaves per parcel

$$\sum_{q \in \mathcal{P}:(p,q) \in \mathcal{D}} y^t_{(p,q)c} = x^t_{cp}, \quad \forall c \in \mathcal{C}, \forall p \geq 2, p \neq q \in \mathcal{P}, \forall t \in \mathcal{T}$$

$$\sum_{q \in \mathcal{P}:(p,q) \in \mathcal{D}} z^t_{(p,q)c} = x^t_{cp}, \quad \forall c \in \mathcal{C}, \forall p \geq 2, p \neq q \in \mathcal{P}, \forall t \in \mathcal{T}$$

- **Machinery scheduling subtour elimination constraint (Miller-Tucker-Zemlin)**

$$w_p - w_q + MaxP^P y^t_{(p,q)c} \leq MaxP^P - 1, \forall 2 \leq p \neq q \leq P \in \mathcal{P}, \forall c \in \mathcal{C}, \forall t \in \mathcal{T}$$

$$w'_p - w'_q + MaxP^H z^t_{(p,q)c} \leq MaxP^H - 1, \forall 2 \leq p \neq q \leq P \in \mathcal{P}, \forall c \in \mathcal{C}, \forall t \in \mathcal{T}$$

Data Inputs - Study Area for Guayule

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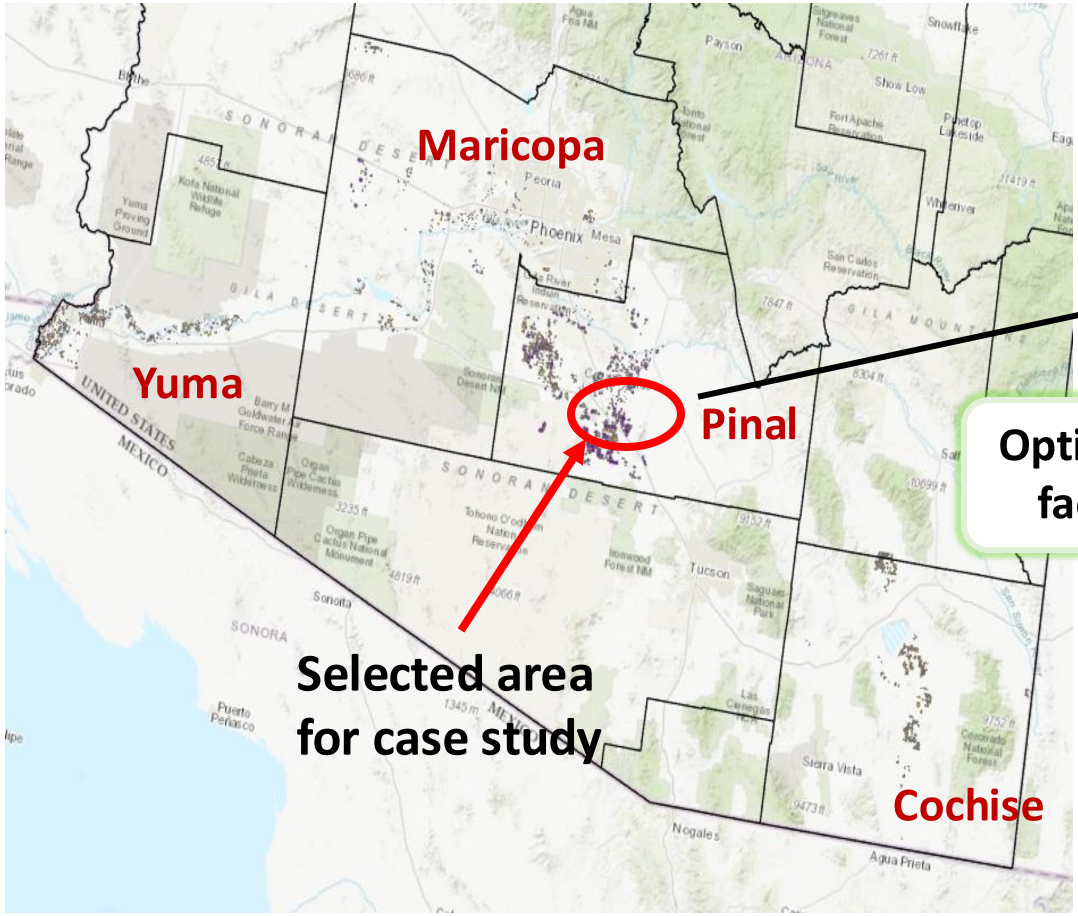
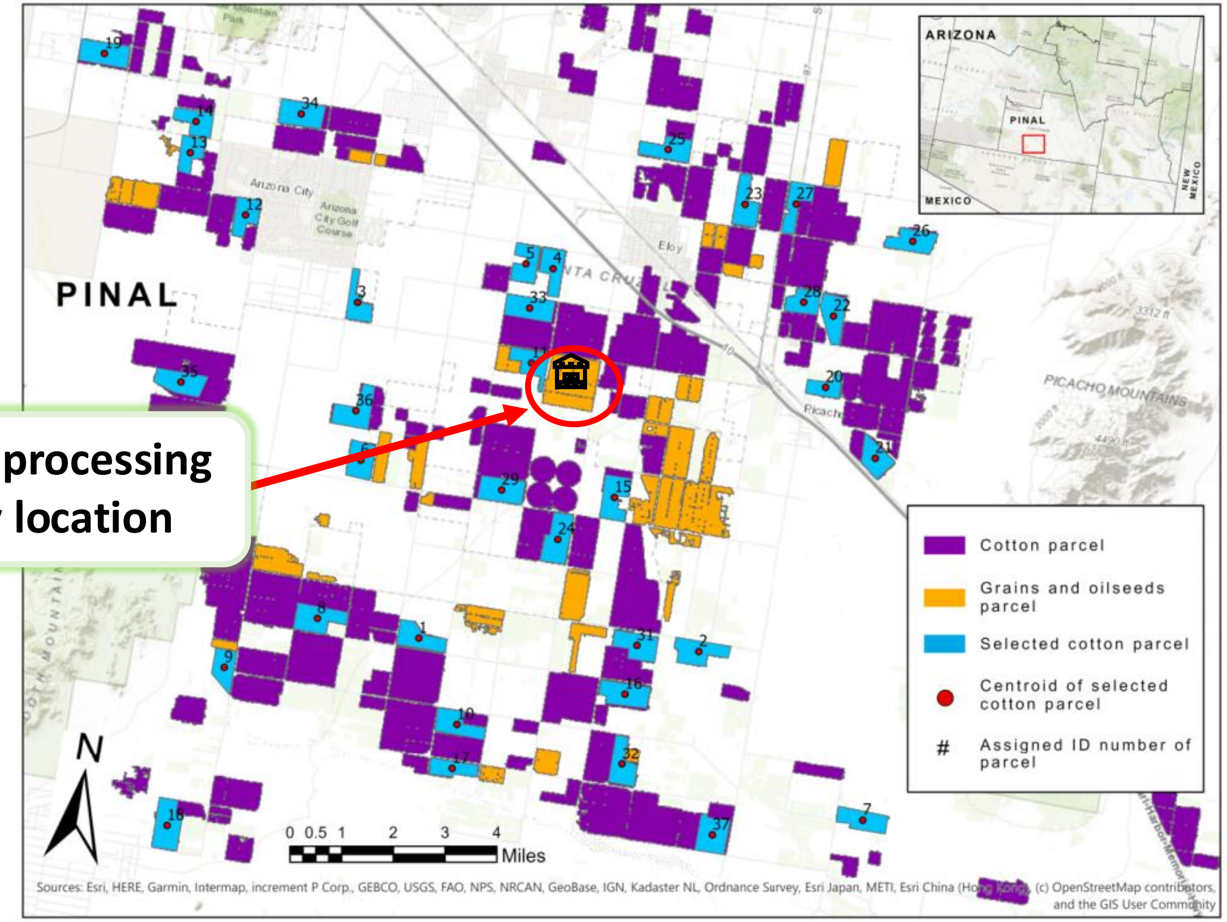


Optimal processing facility location



Guayule

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Input Parameters

Crop rotation	1:2 for guayule and cotton/wheat
Machinery loan amortization	6 years
Interest rate	3.49%
Machinery capacity per harvest season	1,500 acres
Maximum number of parcels per machinery	6
Machinery transportation cost	0.1 USD/mile
Discount rate	0.06
Sale price inflation rate	0.02
Costs inflation rate	0.02
Irrigation water cost	60 USD per acre/foot

Marked in blue obtained from Integrated Guayule Model v3.19 4_14_20_CFS

Otherwise obtained from best online reference identified

Concept	Guayule	Cotton	Wheat
Yield	12 t/acre	1.3 t/acre	1.6 t/acre
Minimum demand (year)	2,456 t	3,063 t	3,769 t
Fertilicers and herbicides	78.7 USD/acre	76.6 USD/acre	62.9 USD/acre
Seed costs	40.5 USD/acre	188.8 USD/acre	66 USD/acre
Sale price	114.6 USD/t	910.2 USD/t	202.2 USD/t
Irrigation water	4.5 acre/foot per acre	5 acre/foot per acre	2 acre/foot per acre

Guayule

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Input Parameters

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Max
Min

Table 3: Pinal Parcels' Acreage

Parcel no.	Acres	Parcel no.	Acres	Parcel no.	Acres	Parcel no.	Acres
1	216.8	11	203.2	21	190.7	31	234.9
2	246.8	12	185.5	22	220.2	32	221.4
3	171.9	13	163.1	23	219.7	33	245.1
4	194.5	14	182.1	24	249.0	34	249.9
5	195.0	15	237.4	25	220.1	35	235.4
6	211.3	16	246.8	26	217.8	36	248.0
7	211.4	17	161.5	27	192.9	37	245.7
8	248.0	18	250.0	28	171.2		
9	178.6	19	247.0	29	249.3		
10	221.3	20	138.6	30	247.0		

Table 4: Guayule, Cotton, and Wheat Machinery

Machinery	Capital cost (USD)	Operational cost (USD/acre)	Tractor	Crop		
125 HP 4WD Tractor	0	-	-	G	C	W
175 HP 4WD Tractor	0	-	-	G	C	W
2-Row Shredder	0	7.1	125 HP	-	C	-
4-Bottom Plow	0	24.2	175 HP	-	C	-
4-Row Lister	0	11.6	175 HP	G	C	-
7-Shank Chisel	0	10.2	175 HP	-	-	W
8-Row Planter	0	6.3	175 HP	G	C	-
8-Row Rolling Cultivator	0	14.1	125 HP	G	C	-
18' Disc	0	12.8	175 HP	G	C	W
Baler	120,000	36.1	125 HP	G	-	-
Bed Shaper	6,500	6.8	175 HP	G	-	-
Boom Sprayer	0	3.1	125 HP	G	C	W
Combine	0	4.6	-	-	-	W
Cotton Picker	0	20.3	175 HP	-	C	-
Drill	0	4.5	125 HP	-	-	W
Fertilizer Spreader	18,000	4.3	125 HP	G	-	-
Float	0	10.9	125 HP	-	C	-
Gin Cotton (Custom)	0	204.4	-	-	C	-
Landplane	18,000	9.9	175 HP	G	-	-
Swathing	75,000	31.7	-	G	-	-
V-Ripper	22,000	19.6	175 HP	G	-	-

Crop: guayule (G), cotton (C), wheat (W)

Guayule

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Implementation

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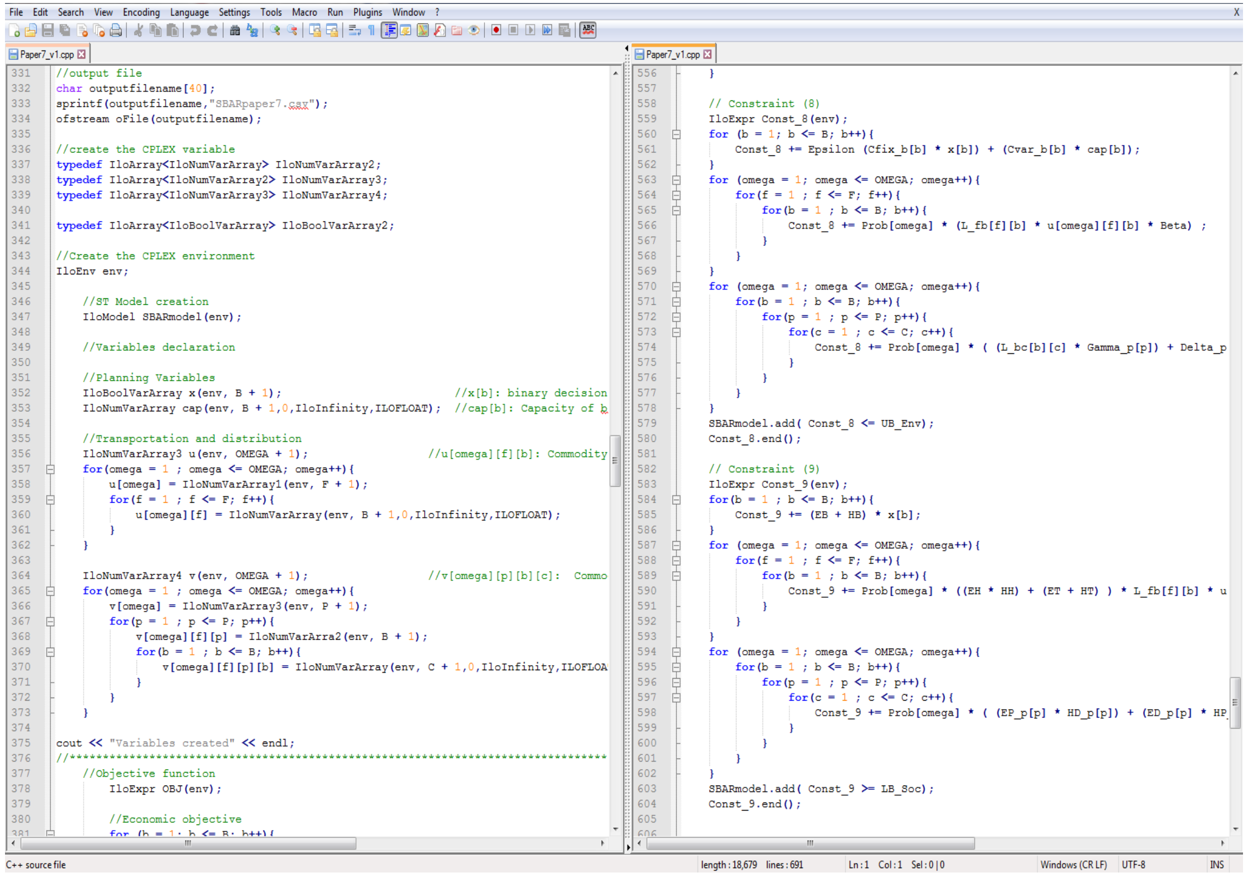
- Implemented in **C++** using **CPLEX** 12.7 via ILOG Concert Technology 2.9, on Intel Haswell V3 24 core processors and 186GB RAM.



Ocelote HPC cluster from the University of Arizona

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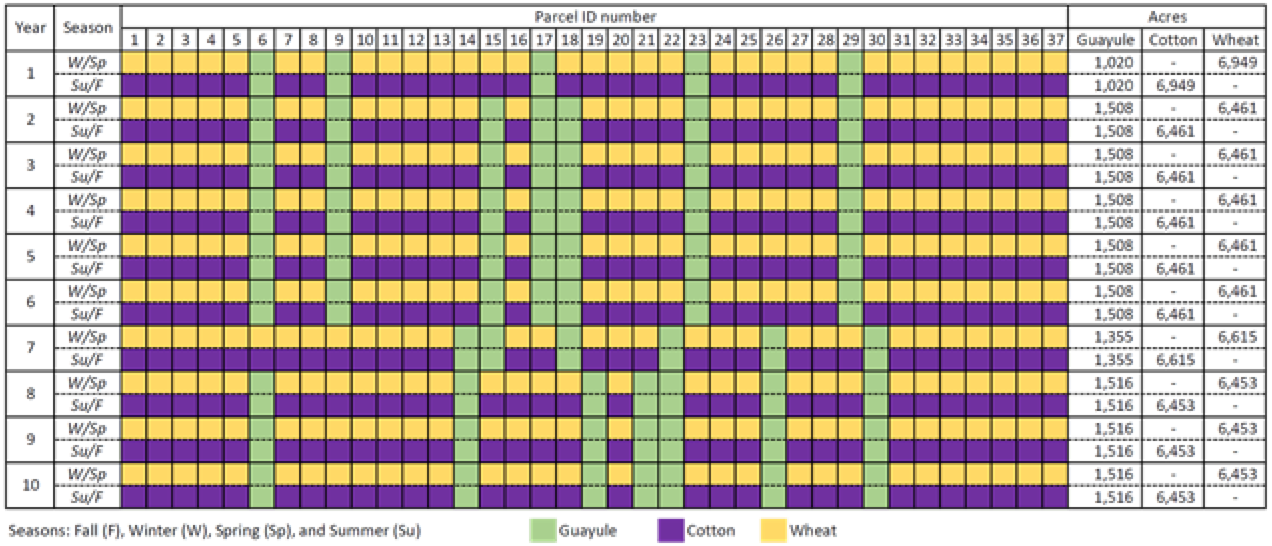
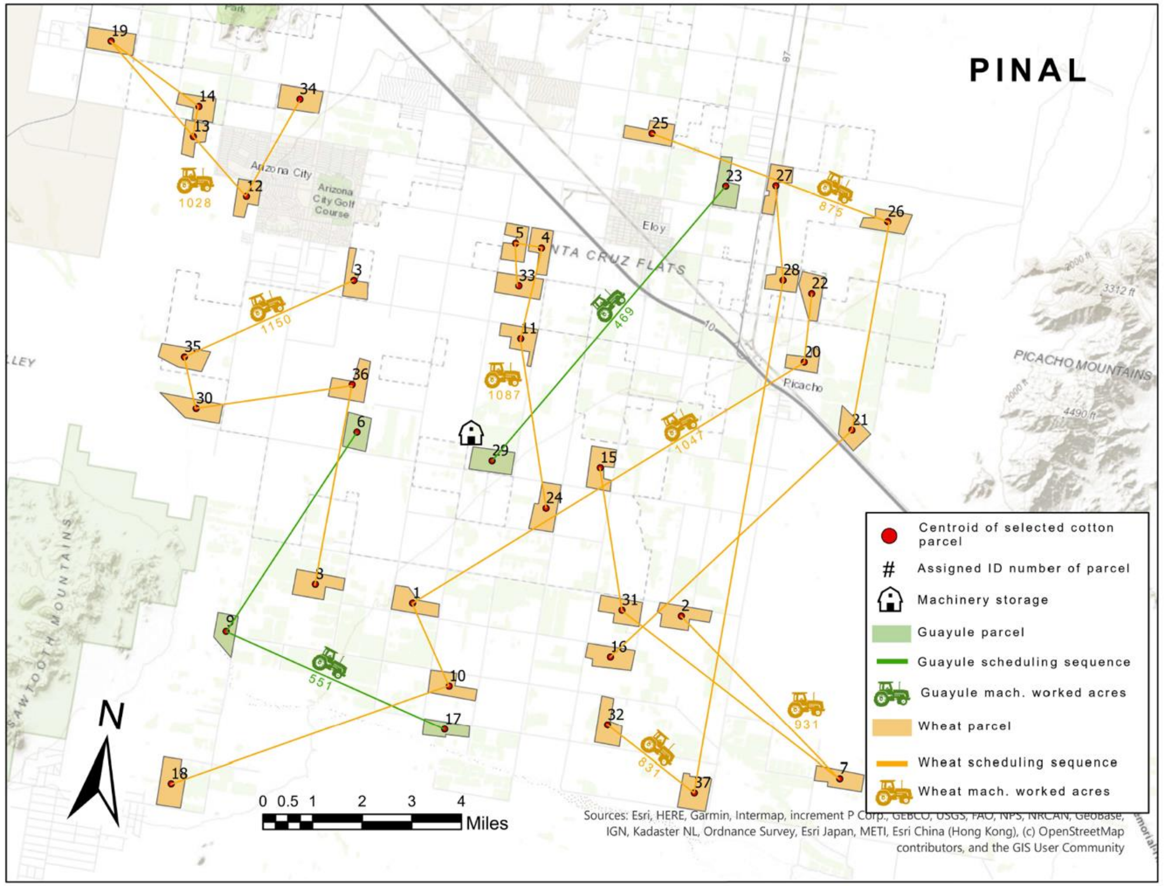
Optimal Production Planning and planting scheduling for Guayule



Year	Season	Guayule (Acres)	Cotton (Acres)	Wheat (Acres)
1	W/Sp	1,020	-	6,949
	Su/F	1,020	6,949	-
2	W/Sp	1,508	-	6,461
	Su/F	1,508	6,461	-
3	W/Sp	1,508	-	6,461
	Su/F	1,508	6,461	-
4	W/Sp	1,508	-	6,461
	Su/F	1,508	6,461	-
5	W/Sp	1,508	-	6,461
	Su/F	1,508	6,461	-
6	W/Sp	1,508	-	6,461
	Su/F	1,508	6,461	-
7	W/Sp	1,355	-	6,615
	Su/F	1,355	6,615	-
8	W/Sp	1,516	-	6,453
	Su/F	1,516	6,453	-
9	W/Sp	1,516	-	6,453
	Su/F	1,516	6,453	-
10	W/Sp	1,516	-	6,453
	Su/F	1,516	6,453	-

Guayule, cotton, and wheat optimal production planning



Guayule, cotton, and wheat optimal planting scheduling of year 1

Results for Guayule

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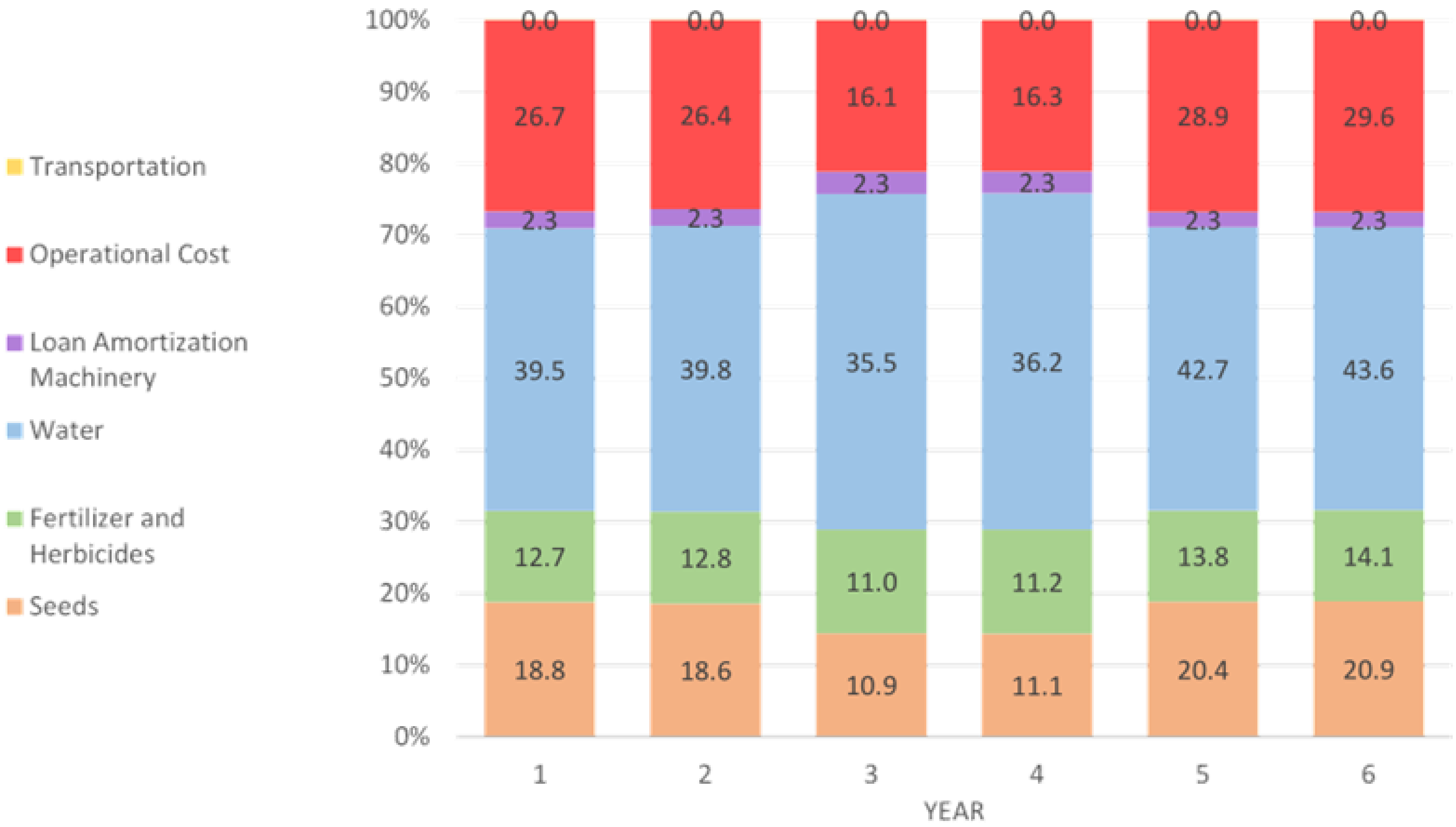
National Institute of Food and Agriculture

Year	1	2	3	4	5	6
Revenue (MUSD)	10.01	10.05	7.86	8.35	10.84	10.71
Total Cost (MUSD)	7.62	7.62	5.78	5.87	8.23	8.42
Gross Profit (MUSD)	2.39	2.44	2.08	2.47	2.60	2.29

Guayule, cotton, and wheat economics

NPV
12.4 million USD



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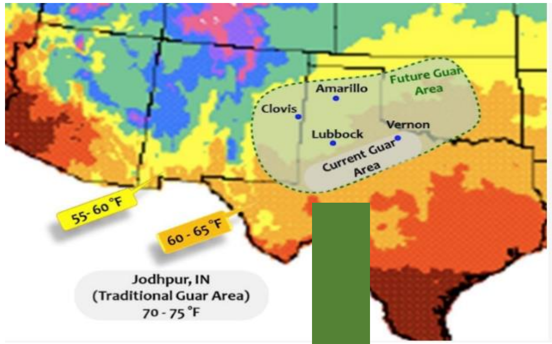
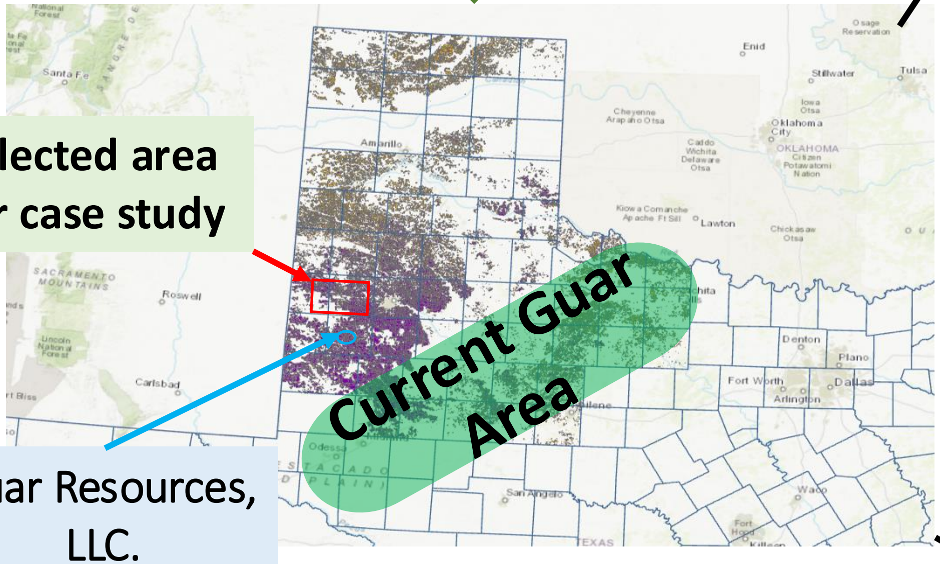
Data Inputs - Study Area for Guar

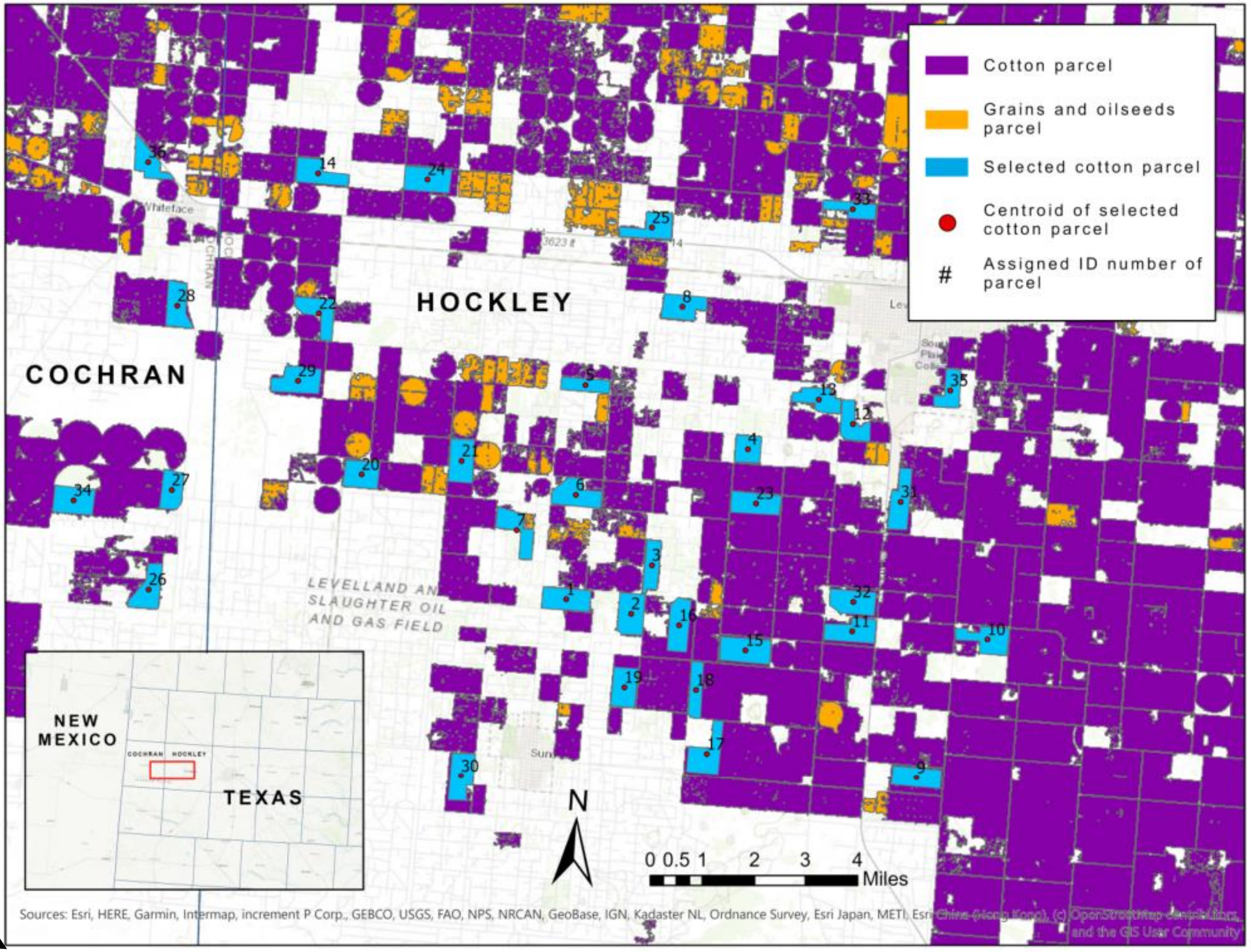




Selected area for case study

Guar Resources, LLC.

807 N 5th St, Brownfield, TX 79316



Guar

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Guar

United States Department of Agriculture

National Institute of Food and Agriculture

Table 1: Cochran and Hockley Parcels' Acreage

Parcel no.	Acres	Parcel no.	Acres	Parcel no.	Acres	Parcel no.	Acres
1	243.1	11	241.6	21	243.6	31	240.4
2	245.1	12	188.5	22	217.6	32	242.5
3	171.9	13	196.4	23	244.6	33	156.0
4	159.7	14	229.7	24	245.7	34	249.7
5	145.4	15	246.8	25	217.4	35	164.2
6	248.0	16	245.3	26	221.2	36	140.5
7	211.7	17	249.9	27	145.7		
8	224.5	18	162.7	28	216.8		
9	225.7	19	98.7	29	247.8		
10	240.1	20	219.1	30	242.2		

Max

Min

Table 2: Guar and Cotton Machinery

Machinery	Capital cost (USD)	Operational cost (USD/acre)	Tractor	Crop	
125 HP 4WD Tractor	0	-	-	G	C
175 HP 4WD Tractor	0	-	-	G	C
2-Row Shredder	0	7.1	125 HP	-	C
4-Bottom Plow	0	24.2	175 HP	-	C
4-Row Lister	0	11.6	175 HP	-	C
8-Row Planter	0	6.3	175 HP	-	C
8-Row Rolling Cultivator	0	14.1	125 HP	-	C
18' Disc	0	12.8	175 HP	G	C
Boom Sprayer	0	3.1	125 HP	G	C
Cotton Picker	0	20.3	175 HP	-	C
Drill	25,000	4.5	125 HP	G	-
Fert. Sidedress	2,500	0.1	125 HP	G	-
Float	0	10.9	125 HP	-	C
Gin Cotton (Custom)	0	204.4	-	-	C
Moldboard Plow	35,000	9.7	175 HP	G	-
Combine (Custom)	180,000	0.0	-	G	-

Crop: guar (G), cotton (C)

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Input Parameters

Marked in blue obtained from Integrated Guar Model v3.16 5_11_20_HMS

Otherwise obtained from best online reference identified

Crop rotation	1:2 for guar and cotton

Machinery loan amortization	6 years
Interest rate	3.49%
Machinery capacity per harvest season	1,500 acres
Maximum number of parcels per machinery	6
Machinery transportation cost	0.1 USD/mile

Discount rate	0.06
Sale price inflation rate	0.02
Costs inflation rate	0.02

Irrigation water cost	60 USD per acre/foot

Concept	Guar	Cotton
Yield	0.41 t/acre	1.3 t/acre
Minimum demand (year)	158 t	2,907 t
Fertilicers and herbicides	145 USD/acre	76.6 USD/acre
Seed costs	6 USD/acre	188.8 USD/acre
Sale price	492.7 USD/t	910.2 USD/t
Irrigation water	0.8 acre/foot per acre	5 acre/foot per acre

Guar

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SBAR

Optimal Production Planning and planting scheduling for Guar

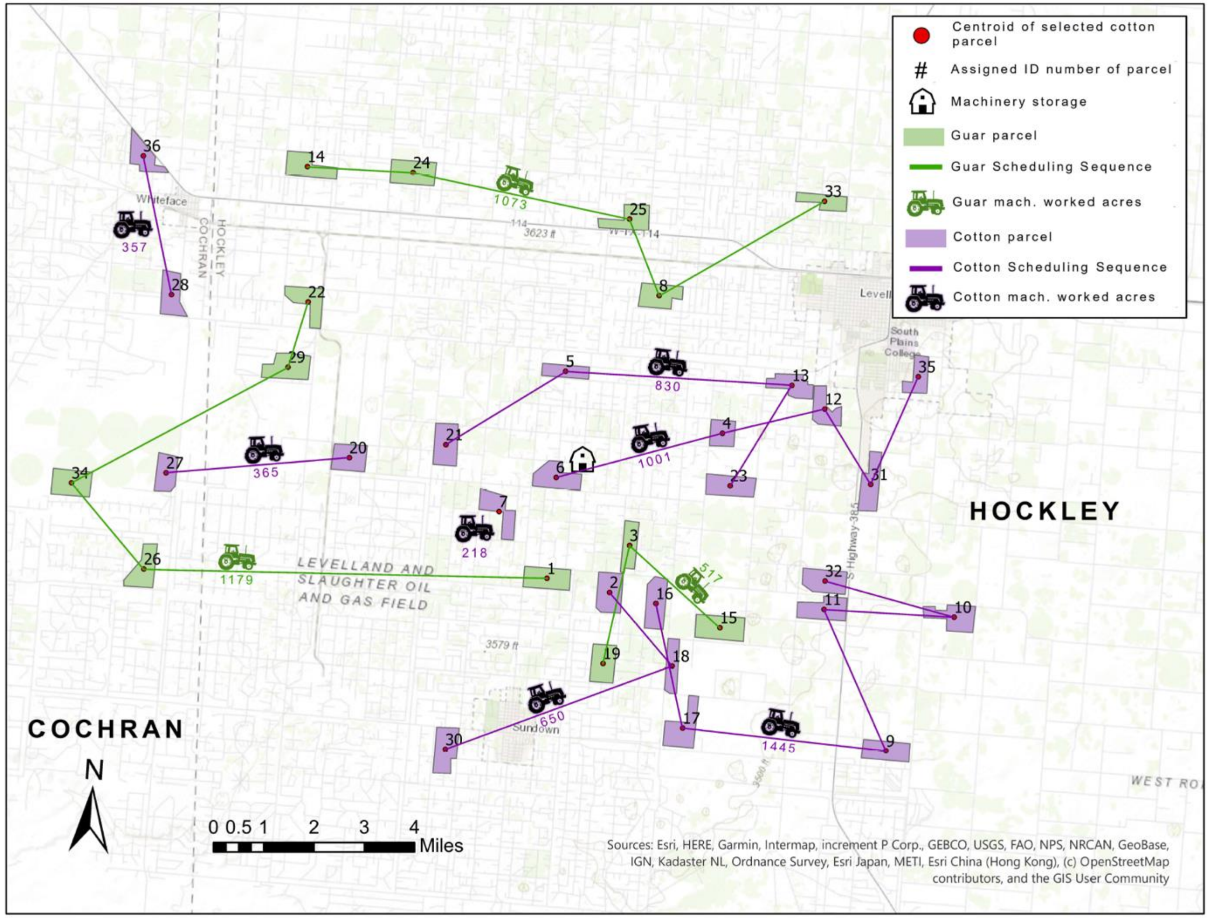
USDA United States Department of Agriculture | National Institute of Food and Agriculture

Year	Acres: Guar	Acres: Cotton
1	524	7,106
2	2,770	4,860
3	4,336	3,294
4	524	7,106
5	2,770	4,860
6	4,336	3,294
7	524	7,106
8	2,770	4,860
9	4,336	3,294
10	524	7,106

Parcel ID number: 1–36

Guar   Cotton

Guar and cotton optimal production planning



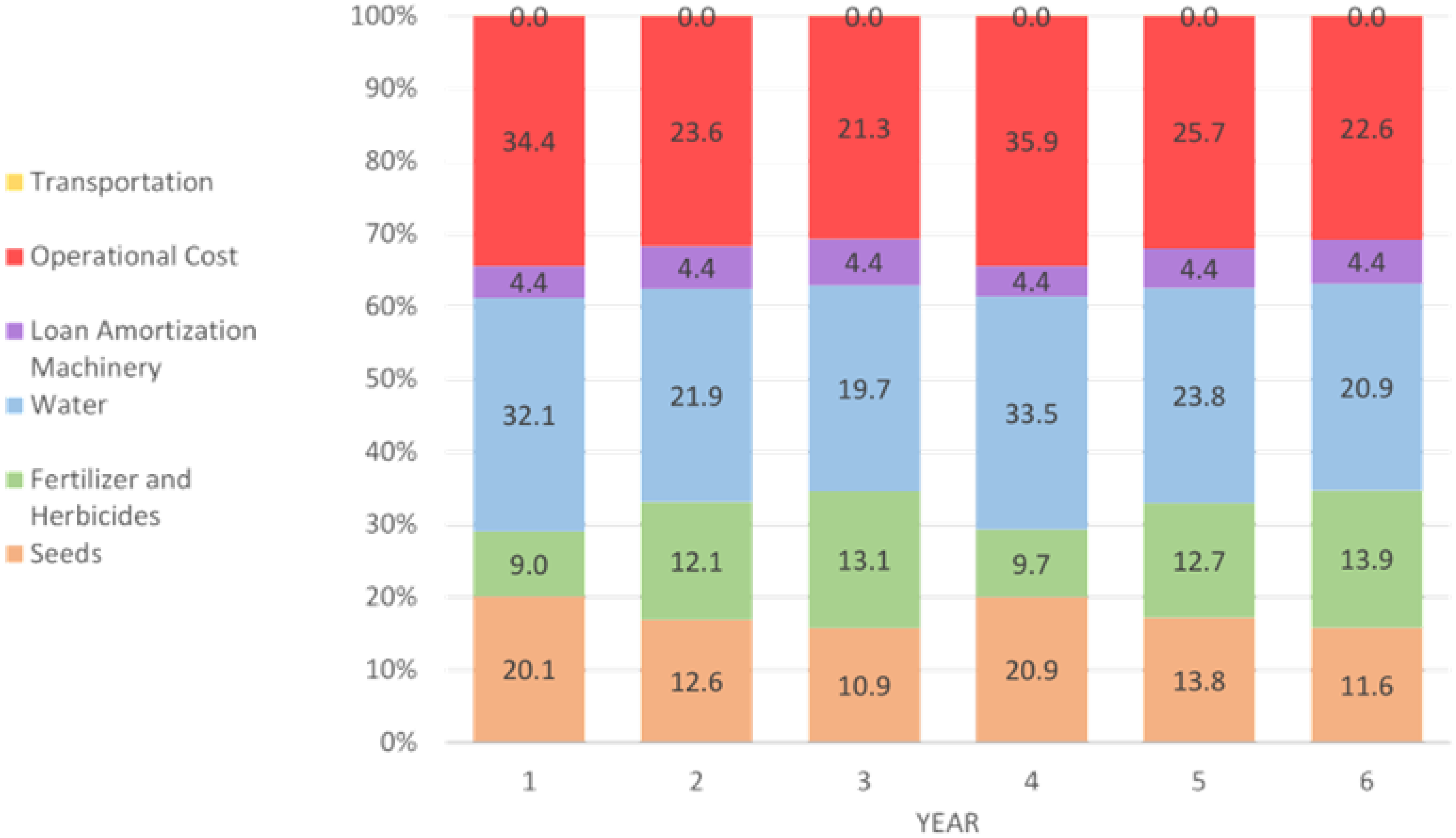
Guar and cotton optimal planting scheduling of year 2

Results for Guar

Year	1	2	3	4	5	6
Revenue (MUSD)	8.62	5.93	5.35	8.99	6.46	5.68
Total Cost (MUSD)	6.96	5.19	4.82	7.26	5.60	5.10
Gross Profit (MUSD)	1.66	0.74	0.53	1.73	0.86	0.58

Guar and cotton economics

NPV
5.4 million USD



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Harvest Planning and Scheduling

USDA United States Department of Agriculture

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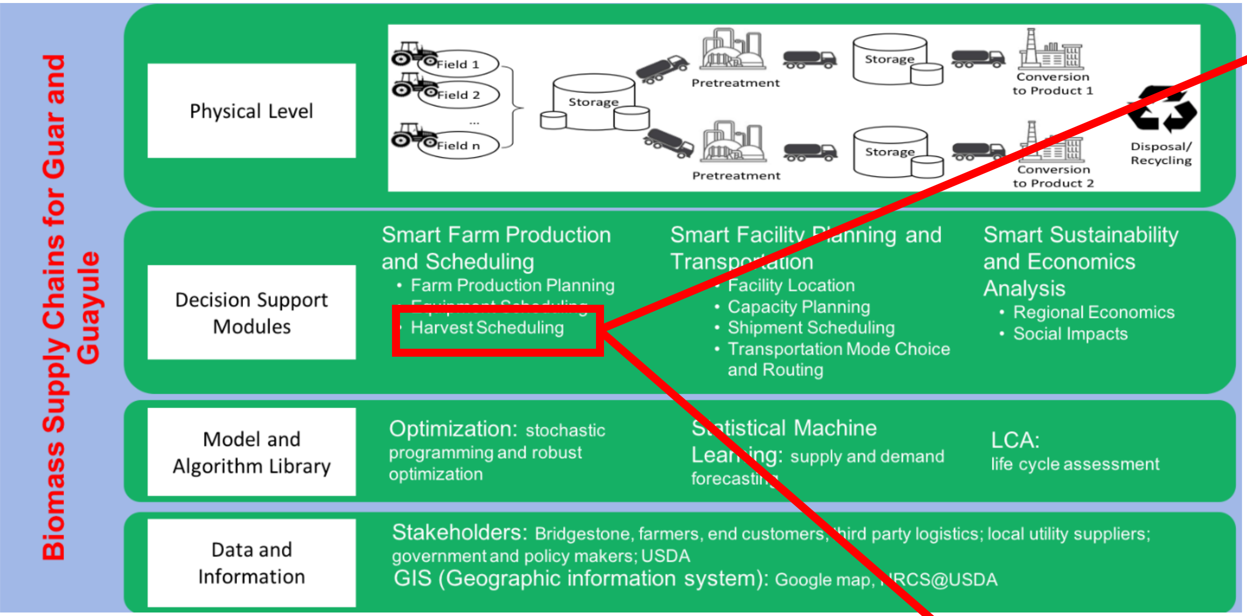
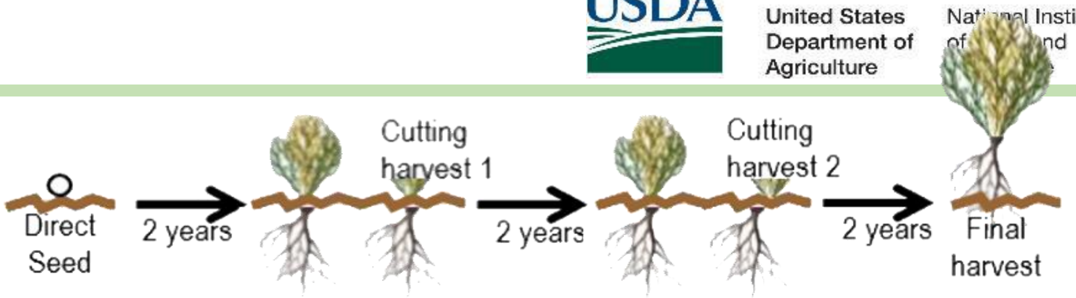




- A perennial 6-year woody shrub which takes approximately 18 months to 2 years to reach harvest size
- Harvest guayule every 2 years within the 6-year period
- Intermediate harvests are possible at the end of year one, but the highest rubber content is found in year two harvests
- Irrigation can shorten the time until harvest
- Excess water is harmful to guayule plants of all ages

Guayule

When to harvest?

How to harvest?

How much to harvest in one field?

- *Yao, S., Fan, N., Seavert, C., & Teegerstrom, T. (2023). Demand-Driven Harvest Planning and Machinery Scheduling for Guayule. In Operations Research Forum, Operations Research Forum, Vol. 4(9), pp 1–25. doi: 10.1007/s43069-022-00192-2.*

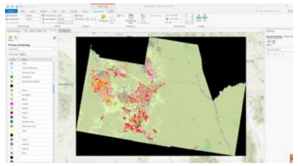
Module III - Harvest Planning and Scheduling

United States Department of Agriculture
National Institute of Food and Agriculture

- Costs
  - Rent
  - Operation
  - Transportation
  - Penalty
- Harvesting Demand
- Characteristics of crops
- 37 fields located in Pinal, AZ

SBAR Research Input

- Crop's acreage
- Crop's location



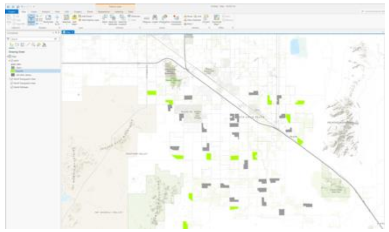
CropScape Input

- Irrigation districts
- Groundwater conservation
- Medium and high development
- Railroad
- High way and primary roads

GIS Layers Input

Python & Gurobi

ArcGIS Pro 2.9.2

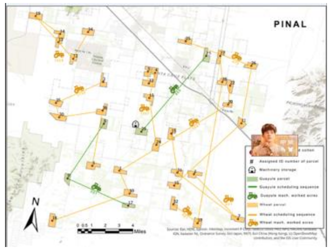


Optimization Model (MILO)

Optimal Solution

- 10-year harvest planning
- Optimal scheduling

- **Case study for guayule harvesting**
- **Crop rotation (guayule, cotton & wheat) for a harvest**
- **Sensitivity analysis on harvest demand**



Harvesting problem for guayule

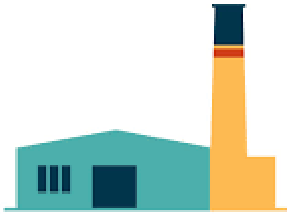
United States Department of Agriculture
National Institute of Food and Agriculture

A complex and comprehensive problem constrained by many factors

- Long-time harvest planning
- Maturity period of the guayule (periodic harvest)
- Risk of quality loss (due to weather conditions, uncertainty and variability)
- Resource limitations (like land capacity/productivity, available machines or labors)
- Scheduling problem
- Late penalties for not harvesting on time

Extreme weather

Quality loss

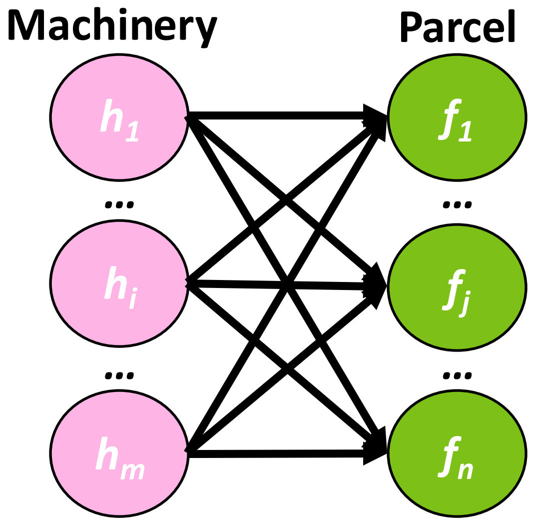


Limited capacity

Harvest scheduling

Optimization Modeling

USDA United States Department of Agriculture
National Institute of Food and Agriculture

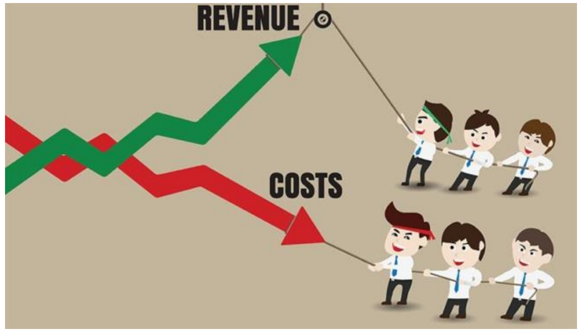


Methods

- (Deterministic) Mixed-integer linear optimization (MILO)
- Decompose harvest planning into different harvest seasons
- Time window indicating the best harvest time during one harvest season
- Determine the optimal harvest scheduling for each harvest season

Assumptions

- Suppose a time period is one week, harvesting each guayule field f in a time window $[R_f^k, D_f^k]$ during the harvest season k
- Penalties incurred for not harvesting before the due date D_f^k
- All harvesters depart from the warehouse/facility at the beginning of the harvest season and return to it at the end of one harvest season
- Harvesters move between fields at the end of time periods



Goals

- **When** — determine the harvesting time for each guayule parcel
- **How** — determine the optimal machinery harvesting scheduling
- **How much** — determine the fraction of each field to be harvested at each time

Optimization Model of Module III - Objective Function

Goal: Minimize the total cost

$$\text{TotalCost} = \text{RentCost} + \text{OperationCost} + \text{TransportationCost} + \text{PenaltyCost}$$

$$\text{RentCost} = \sum_{k \in K} \sum_{h \in H} \boxed{C_h} u_h^k$$

Ownership/Rent cost of harvester h

$$\text{OperationCost} = \sum_{k \in K} \sum_{t \in T} \sum_{f \in F} \boxed{C^o A_f} x_{ft}^k$$

Operational cost for field f
(including labor, repairs, maintenance, fuel, and lube)

$$\text{TransportationCost} = \sum_{k \in K} \sum_{t \in T} \sum_{h \in H} \sum_{i \in F} \sum_{j \in F} \boxed{C^r d_{(i,j)}} y_{ht,(i,j)}^k$$

Route cost from i to j

$$\text{PenaltyCost} = \sum_{k \in K} \sum_{f \in F} \boxed{C_f^p A_f I_f^k} \cdot \max\{e_f^k - D_f^k, 0\}$$

Penalty cost for not harvesting on time

Optimization Model of Module III - Parameters & Variables

SBAR

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Table 1: Sets and indices

F:	Set of fields, indexed by f
H:	Set of harvesters, indexed by h
T:	Set of time periods, indexed by t (e.g. 1st week of harvesting)
K:	Set of harvest seasons, indexed by k (e.g. fall of the second year)

Table 2: Parameters

C_h:	Ownership/Rent cost of harvester h (\$/harvest season)
C^o:	Unit machinery operational cost (including labor, repairs, maintenance, fuel, and lube) during harvesting one field (\$/acre).
C^r:	Unit route/transportation cost (\$/mile)
$d_{(i,j)}$:	Distance between field i and j (mile)
C_f^p:	Penalty cost incurred for not harvesting field f on time (\$/(acre*period))
R_f^k:	Ready date of field f for harvest season k
D_f^k:	Due date of field f for harvest season k
A_f:	Acres for field f (acre)
M_f:	Maximum number of machines that can harvest field f in a given period
M^{Cap}:	Harvesting capacity of one harvester per length of harvest season (acre)
I_f^k:	Binary values indicate whether field f should be harvested in the harvest season k

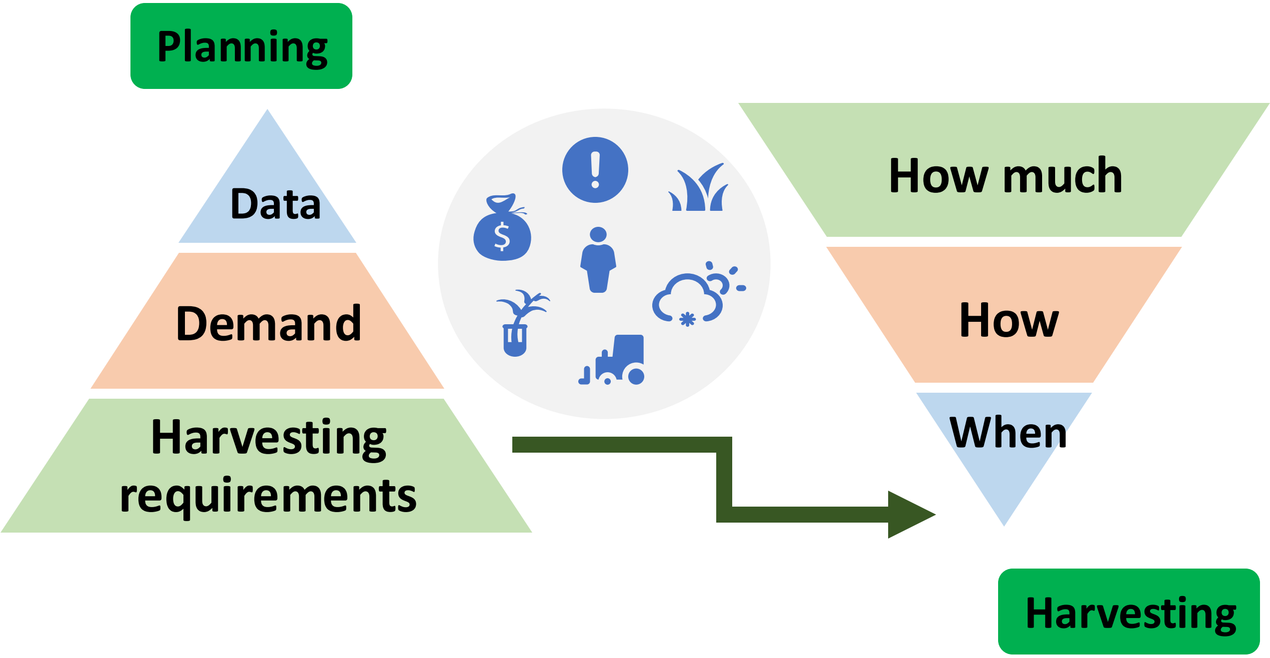
Table 3: Variables

$u_h^k \in \{0,1\}$:	$u_h^k = 1$ if harvester h is used in harvest season k
$x_{ft}^k \in \{0,1\}$:	$x_{ft}^k = 1$ if field f is harvested at period t in harvest season k
$y_{ht,(i,j)}^k \in \{0,1\}$:	$y_{ht,(i,j)}^k = 1$ if harvester h move from field i to j at the end of period t of harvest season k
$z_{hft}^k \in \{0,1\}$:	$z_{hft}^k = 1$ if harvester h for field f is added at period t in harvest season k
$\alpha_{hft}^k \in [0,1]$:	Harvesting fraction for field f using harvester h in period t of harvest season k
$s_f^k \in \{0,\ldots,\lvert T\rvert\}$:	Harvest starting period for field f in harvest season k
$e_f^k \in \{0,\ldots,\lvert T\rvert\}$:	Harvest ending period for field f in harvest season k

$x_{ft}^k, [s_f^k, e_f^k]$ ➡ **When to harvest?**

$y_{ht,(i,j)}^k$ ➡ **How to harvest?**

α_{hft}^k ➡ **How much to harvest in one field?**



Optimization Model of Module III - Constraints

United States Department of Agriculture
National Institute of Food and Agriculture

Harvesting requirements, resource demands & capacity

Harvesting requirements

$$\sum_{f\in F} z^k_{hft} \le 1,\ \forall h,t,k$$

$$\sum_{h\in H} z^k_{hft} \le M_f x^k_{ft},\ \forall f,t,k$$

$$z^k_{hft} = \lceil \alpha^k_{hft} \rceil,\ \forall h,f,t,k$$

$$z^k_{hft} \le u^k_h,\ \forall h,f,t,k$$

$$z^k_{hft} \le x^k_{ft},\ \forall h,f,t,k$$

$$x^k_{ft} \le \sum_{h\in H} z^k_{hft},\ \forall f,t,k$$

Distribution

$$\sum_{t\in T}\sum_{h\in H} \alpha^k_{hft} = I^k_f,\ \forall f,k$$

Time demand

$$x^k_{ft} = 0,\ \forall f,k,t < R^k_f$$

$$x^k_{ft} \le I^k_f \le \sum_{t\in T} x^k_{ft},\ \forall f,t,k$$

Capacity

$$M^{Cap} u^k_h \ge \sum_{f\in F}\sum_{t\in T} A_f \alpha^k_{hft},\ \forall h,k$$

Time window and transportation constraints

Time window requirements

$$R^k_f \le s^k_f \le t + |T|\cdot(1 - x^k_{ft}),\ \forall f,t,k$$

$$e^k_f \ge t x^k_{ft},\ \forall f,t,k$$

$$s^k_f \le e^k_f,\ \forall f,k$$

$$\sum_{t\in T} x^k_{ft} \le e^k_f - s^k_f + 1,\ \forall f,k$$

Transportation constraints

$$\sum_{j\in F} y^k_{h0,(0,j)} = u^k_h,\ \forall h,k$$

$$\sum_{j\in F} y^k_{hT,(j,0)} = u^k_h,\ \forall h,k$$

$$\sum_{j\in F} y^k_{h(t-1),(j,f)} = \sum_{j\in F} y^k_{ht,(f,j)},\ \forall h,f,t,k$$

$$z^k_{hft} \le \sum_{j\in F} y^k_{ht,(f,j)} \le I^k_f,\ \forall h,f,t,k$$

$$\sum_{i\in F}\sum_{j\in F} y^k_{ht,(i,j)} \le u^k_h,\ \forall h,t,k$$

Limitations on decision variables

Binary $u^k_h, x^k_{ft}, y^k_{ht,(i,j)}, z^k_{hft} \in \{0,1\},\ \forall h,f,t,k$

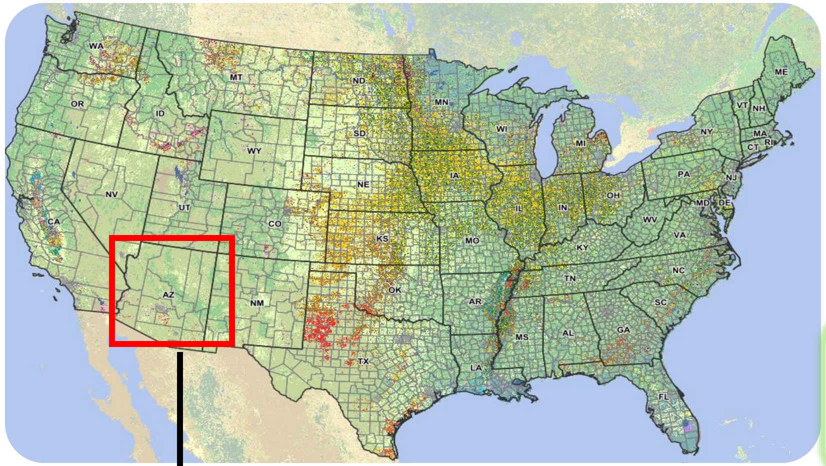
Continuous $\alpha^k_{hft} \in [0,1],\ \forall h,f,t,k$

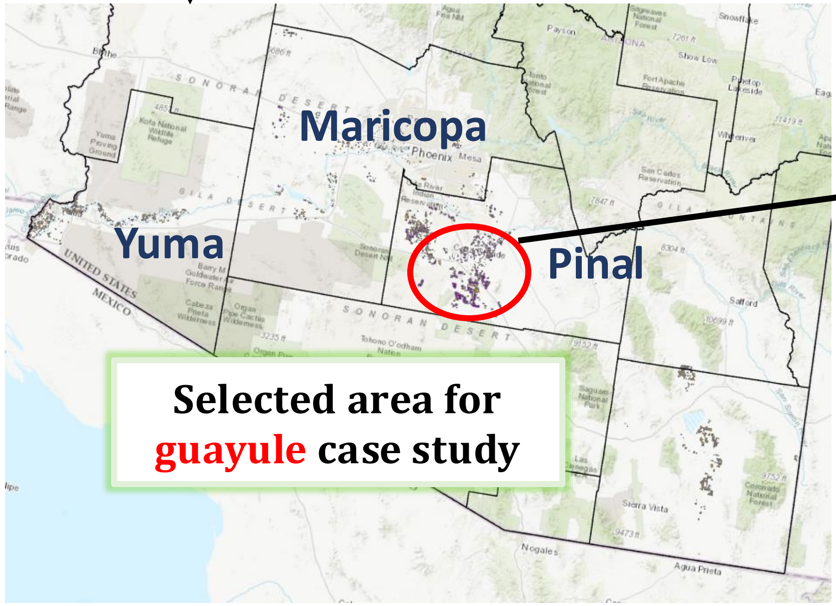
Integer $s^k_f, e^k_f \in \{0,\dots,|T|\},\ \forall f,k$

Data Inputs - Selected Farms

United States Department of Agriculture
National Institute of Food and Agriculture

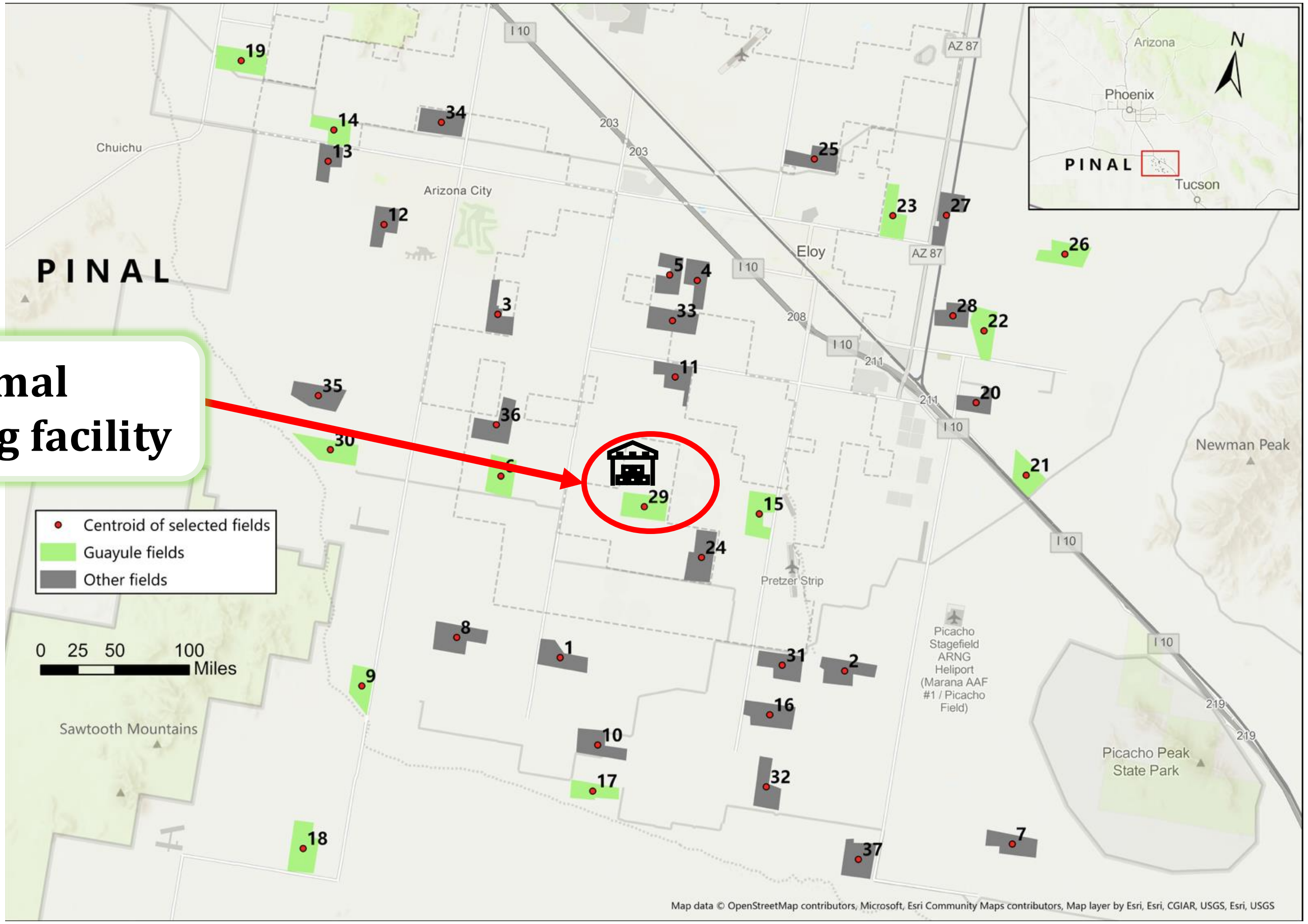
Study Area





Selected area for guayule case study

Optimal processing facility



GIS information on 13 guayule fields located in Pinal County, AZ

SBAR

Data Inputs - Selected Farms

USDA United States Department of Agriculture
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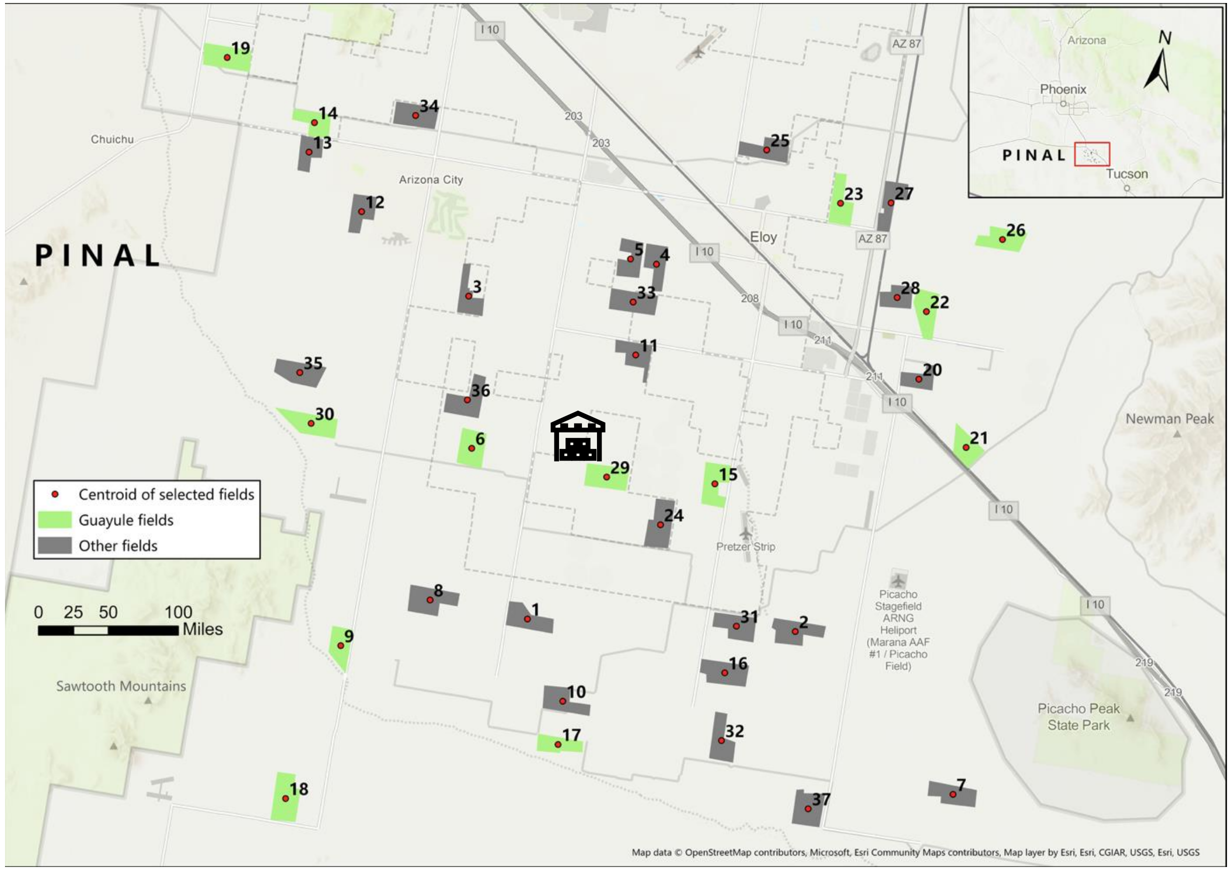
Selected Parcel

Pinal County Selected Parcels' Acreage (13 guayule parcels)

Parcel no.	Acres	Parcel no.	Acres	Parcel no.	Acres	Parcel no.	Acres
1	216.8	11	203.2	21	190.7	31	234.9
2	246.8	12	185.5	22	220.2	32	221.4
3	171.9	13	163.1	23	219.7	33	245.1
4	194.5	14	182.1	24	249.0	34	249.9
5	195.0	15	237.4	25	220.1	35	235.4
6	211.3	16	246.8	26	217.8	36	248.0
7	211.4	17	161.5	27	192.9	37	245.7
8	248.0	18	250.0	28	171.2		
9	178.6	19	247.0	29	249.3		
10	221.3	20	138.6	30	247.0		

13 guayule parcels



Data Inputs - from production planning to harvest planning

Year	Season	Field Number													Acres
		6	9	14	15	17	18	19	21	22	23	26	29	30	Guayule
1	W/Sp														1020
	Su/F														1020
2	W/Sp														1508
	Su/F														1508
3	W/Sp														1508
	Su/F														1508
4	W/Sp														1508
	Su/F														1508
5	W/Sp														1508
	Su/F														1508
6	W/Sp														1508
	Su/F														1508
7	W/Sp														1355
	Su/F														1355
8	W/Sp														1516
	Su/F														1516
9	W/Sp														1516
	Su/F														1516
10	W/Sp														1516
	Su/F														1516

Year	Season	Field Number													Acres
		6	9	14	15	17	18	19	21	22	23	26	29	30	Guayule
1	W/Sp														0
	Su/F														0
2	W/Sp														0
	Su/F														1020
3	W/Sp														0
	Su/F														487
4	W/Sp														0
	Su/F														1020
5	W/Sp														0
	Su/F														487
6	W/Sp														0
	Su/F														1020
7	W/Sp														0
	Su/F														487
8	W/Sp														0
	Su/F														867
9	W/Sp														0
	Su/F														649
10	W/Sp														0
	Su/F														867

Seasons: Winter (W), Spring (Sp), Fall (F), and Summer (Su)

Guayule growing seasons

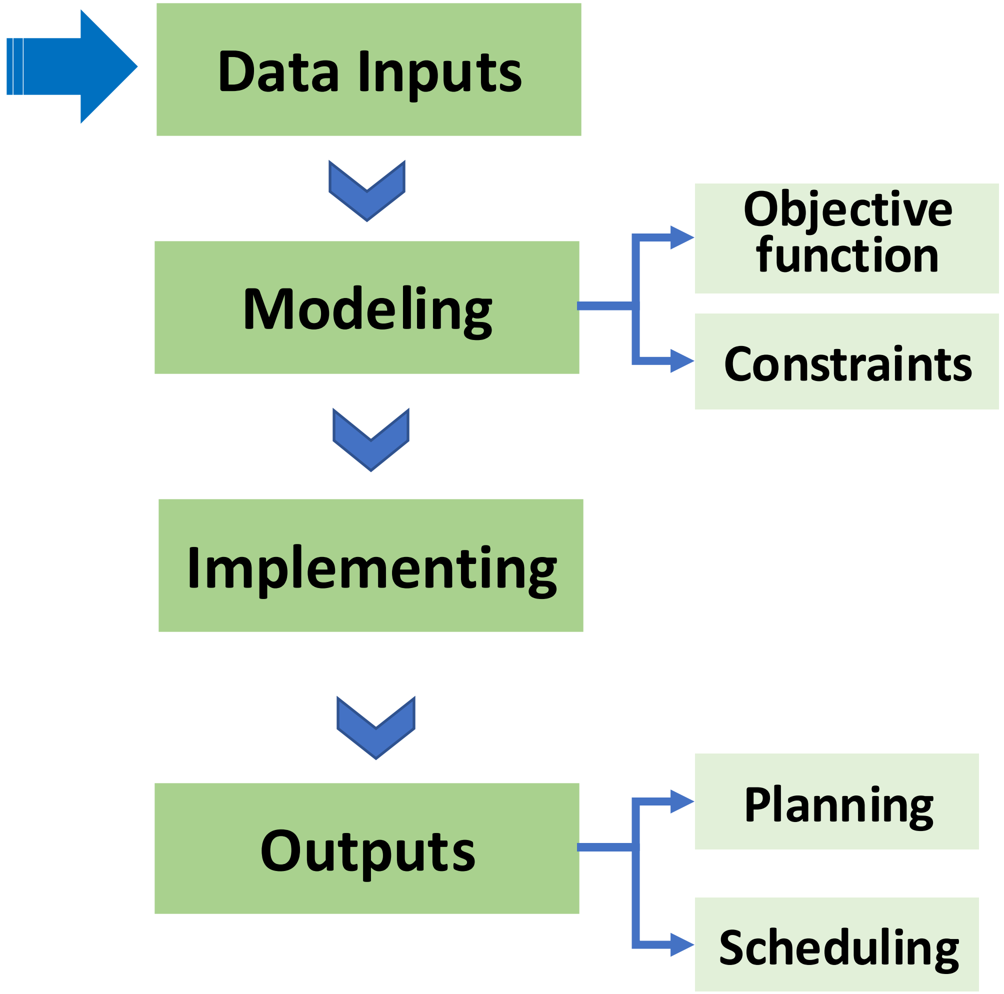
Guayule harvesting seasons

Guayule growing and harvesting seasons based on the previous research

- D. A. Zuniga Vazquez, N. Fan, T. Teegerstrom, C. Seavert, H.M. Summers, E. Sproul, and J.C. Quinn (2021). Optimal Production Planning and Machinery Scheduling for Semi-Arid Farms, *Computers and Electronics in Agriculture*, 187, 106288, doi: 10.1016/j.compag.2021.106288, 2021.

Data Inputs - parameter settings (for guayule)

Parameters	Value
Max # of harvesters $\|H\|$	7
Harvest seasons $\|K\|$	9 seasons
Max time period $\|T\|$	7 weeks
Rent costs	50,000 USD/year
Operational costs	13.1 USD/acre
Transportation costs	3.7 USD/mile
Penalty costs	100 USD/(period*acre)
Harvester capacity	1,500 acres/season
[ready date, due date]	[1,3] (first three weeks)
Facility location	Location 29



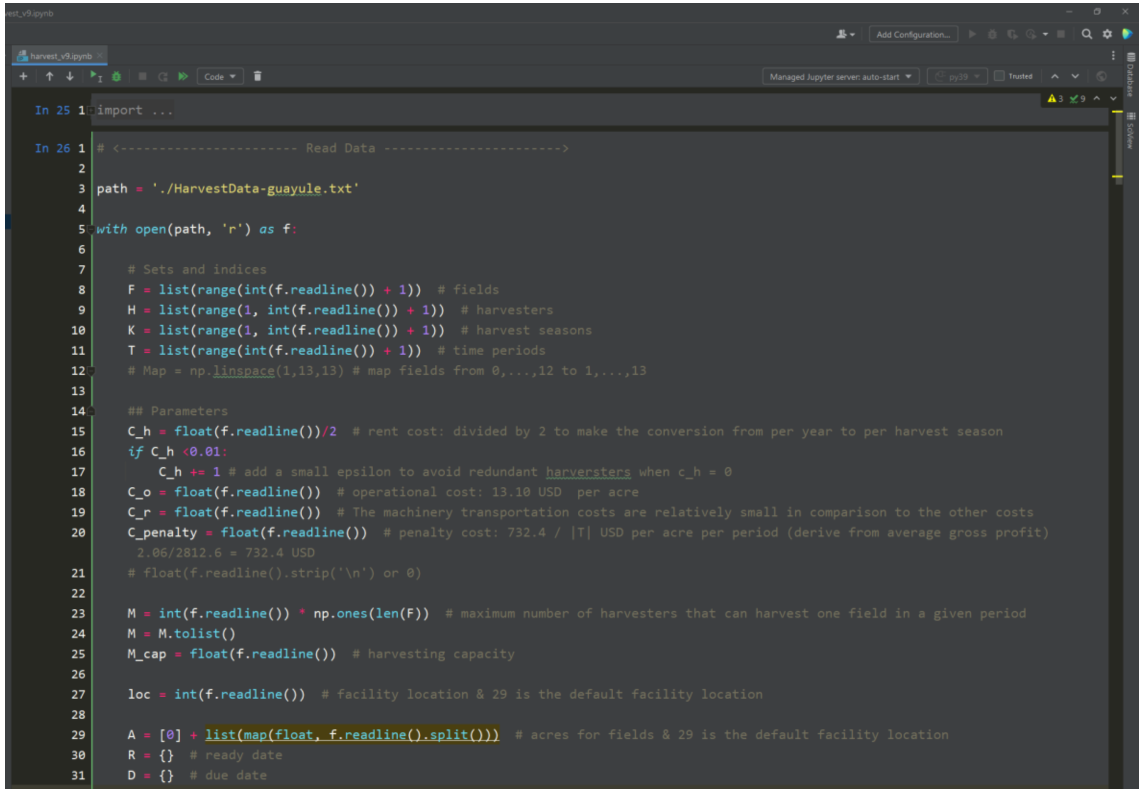
- D. A. Zuniga Vazquez, N. Fan, T. Teegerstrom, C. Seavert, H.M. Summers, E. Sproul, and J.C. Quinn (2021). Optimal Production Planning and Machinery Scheduling for Semi-Arid Farms, *Computers and Electronics in Agriculture*, 187, 106288, doi: 10.1016/j.compag.2021.106288, 2021.
- Zuniga Vazquez, D., Sun, O., Fan, N., Sproul, E., Summers, H., Quinn, J., Khanal, S., Gutierrez, P., Mealing, V., Landies, A., Seavert, C., Teegerstrom, T., & Evancho, B. (2021). Integrating environmental and social impacts into optimal design of guayule and guar supply chains. *Computers & Chemical Engineering*, 146, 107223. doi:10.1016/j.compchemeng.2021.107223.

Implementation

Data Processing

- The proposed model is implemented in **Python 3.9.6** using **Gurobi 9.5.0** with default settings and all computations are performed on a Linux server running CentOS 7 with one AMD EPYC 7642 48-Core processor (2.3GHz) and 512GB memory.

HPC cluster from the University of Arizona



Implementing an optimization model in Python

Guayule Harvesting Results

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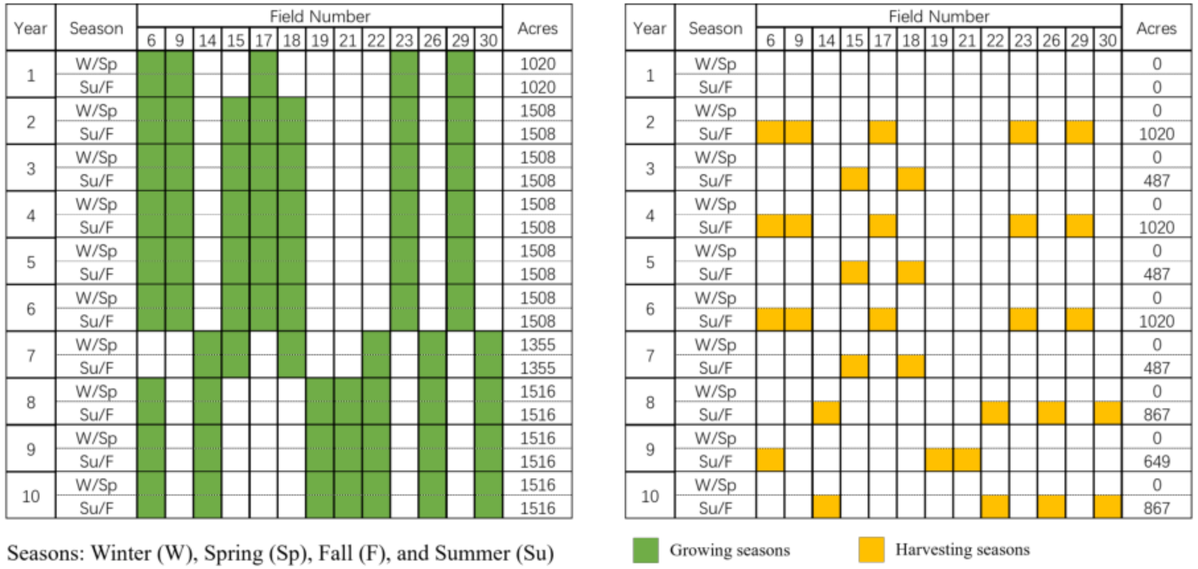
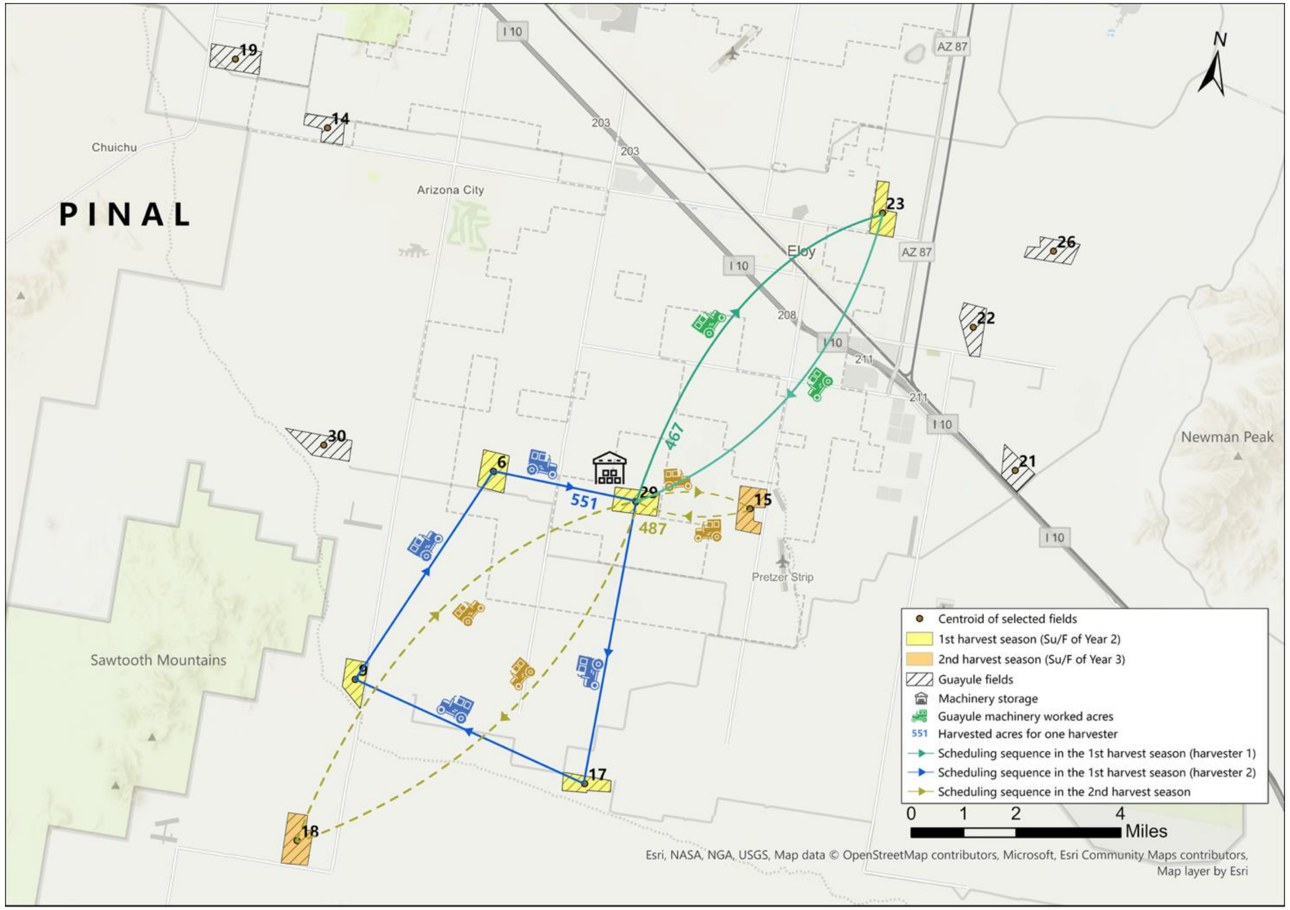


Guayule growing and harvesting seasons

Table 4: Guayule cost breakdown ($1000 USD)

	Year	1	2	3	4	5	6	7	8	9	10	Total Cost
Guayule Costs	Rent Cost	0.00	50.00	25.00	50.00	25.00	50.00	25.00	25.00	25.00	25.00	300.00
	Operational Cost	0.00	13.37	6.39	13.37	6.39	13.37	6.39	11.36	8.50	11.36	90.47
	Transportation Cost	0.00	0.16	0.12	0.16	0.12	0.16	0.12	0.24	0.20	0.24	1.49
	Penalty Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.21	0.00	18.21	36.43
	Total Cost	0.00	63.52	31.50	63.52	31.50	63.52	31.50	54.81	33.70	54.81	428.39



Guayule harvest scheduling of the first two harvest seasons

Guayule Harvesting Results

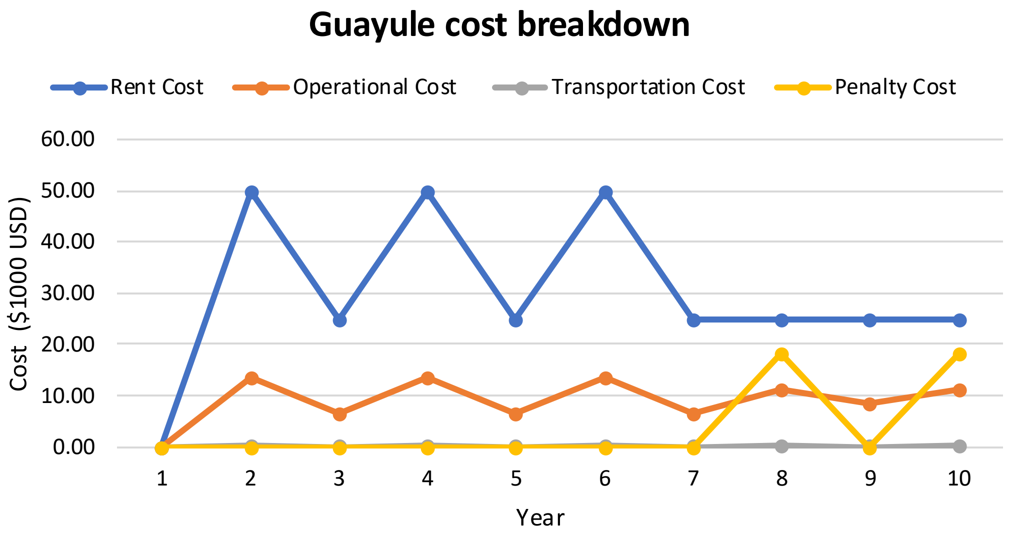
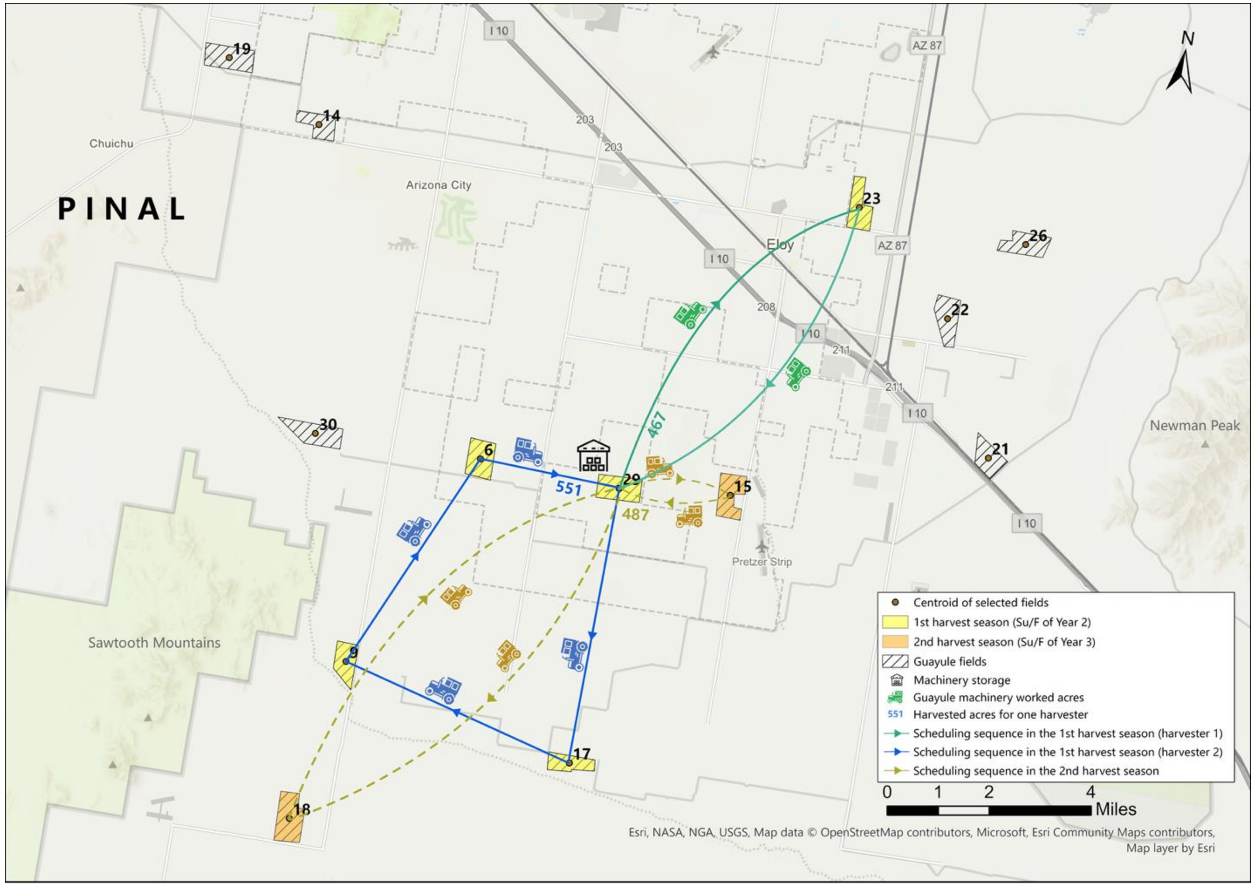


Table 4: Guayule cost breakdown ($1000 USD)

	Year	1	2	3	4	5	6	7	8	9	10	Total Cost
Guayule Costs	Rent Cost	0.00	50.00	25.00	50.00	25.00	50.00	25.00	25.00	25.00	25.00	300.00
	Operational Cost	0.00	13.37	6.39	13.37	6.39	13.37	6.39	11.36	8.50	11.36	90.47
	Transportation Cost	0.00	0.16	0.12	0.16	0.12	0.16	0.12	0.24	0.20	0.24	1.49
	Penalty Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.21	0.00	18.21	36.43
	Total Cost	0.00	63.52	31.50	63.52	31.50	63.52	31.50	54.81	33.70	54.81	428.39



Guayule harvest scheduling of the first two harvest seasons

Crop rotation (guayule, cotton & wheat) for a harvest

United States Department of Agriculture
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- **Considering 37 fields located in Pinal County, AZ**
- **Other parameters remain the same as guayule**

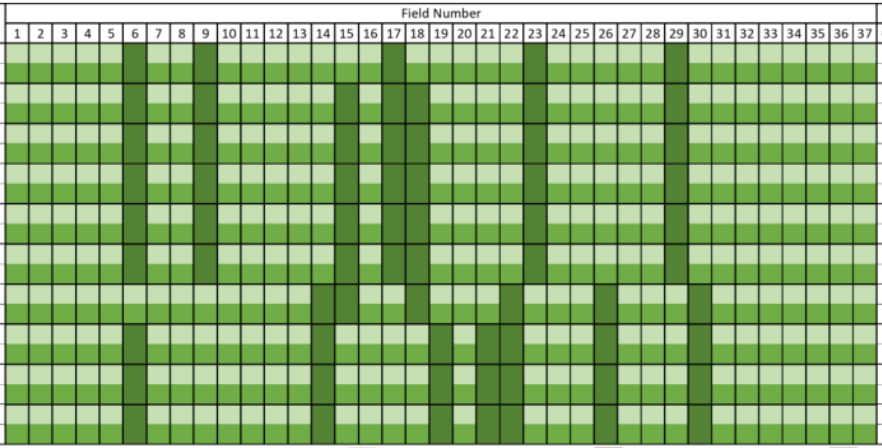
Parameters (cotton)	Value
Harvest seasons $\|K\|$	9 seasons
Rent costs	0 USD/year
Operational costs	73.5 USD/acre
Transportation costs	22 USD/mile

Parameters (wheat)	Value
Harvest seasons $\|K\|$	10 seasons
Rent costs	0 USD/year
Operational costs	24.5 USD/acre
Transportation costs	12 USD/mile

- D. A. Zuniga Vazquez, N. Fan, T. Teegerstrom, C. Seavert, H.M. Summers, E. Sproul, and J.C. Quinn (2021). Optimal Production Planning and Machinery Scheduling for Semi-Arid Farms, *Computers and Electronics in Agriculture*, 187, 106288, doi: 10.1016/j.compag.2021.106288, 2021.
- Zuniga Vazquez, D., Sun, O., Fan, N., Sproul, E., Summers, H., Quinn, J., Khanal, S., Gutierrez, P., Mealing, V., Landies, A., Seavert, C., Teegerstrom, T., & Evancho, B. (2021). Integrating environmental and social impacts into optimal design of guayule and guar supply chains. *Computers & Chemical Engineering*, 146, 107223. doi:10.1016/j.compchemeng.2021.107223.

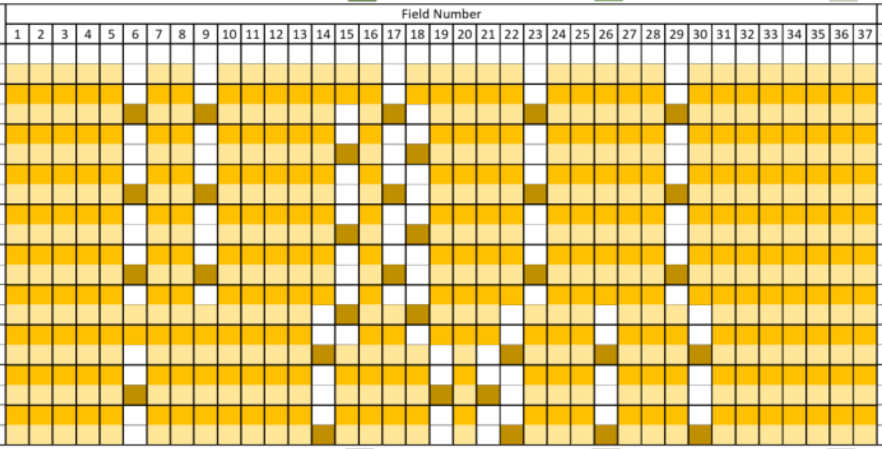
Harvesting Results

From production planning to harvest planning



Year	Season	Acres Guayule	Acres Cotton	Acres Wheat
1	W/Sp	1020	0	6949
	Su/F	1020	6949	0
2	W/Sp	1508	0	6461
	Su/F	1508	6461	0
3	W/Sp	1508	0	6461
	Su/F	1508	6461	0
4	W/Sp	1508	0	6461
	Su/F	1508	6461	0
5	W/Sp	1508	0	6461
	Su/F	1508	6461	0
6	W/Sp	1508	0	6461
	Su/F	1508	6461	0
7	W/Sp	1355	0	6615
	Su/F	1355	6615	0
8	W/Sp	1516	0	6453
	Su/F	1516	6453	0
9	W/Sp	1516	0	6453
	Su/F	1516	6453	0
10	W/Sp	1516	0	6453
	Su/F	1516	6453	0

Seasons: Winter (W), Spring (Sp), Fall (F), and Summer (Su) — Guayule growing seasons; Cotton growing seasons; Wheat growing seasons

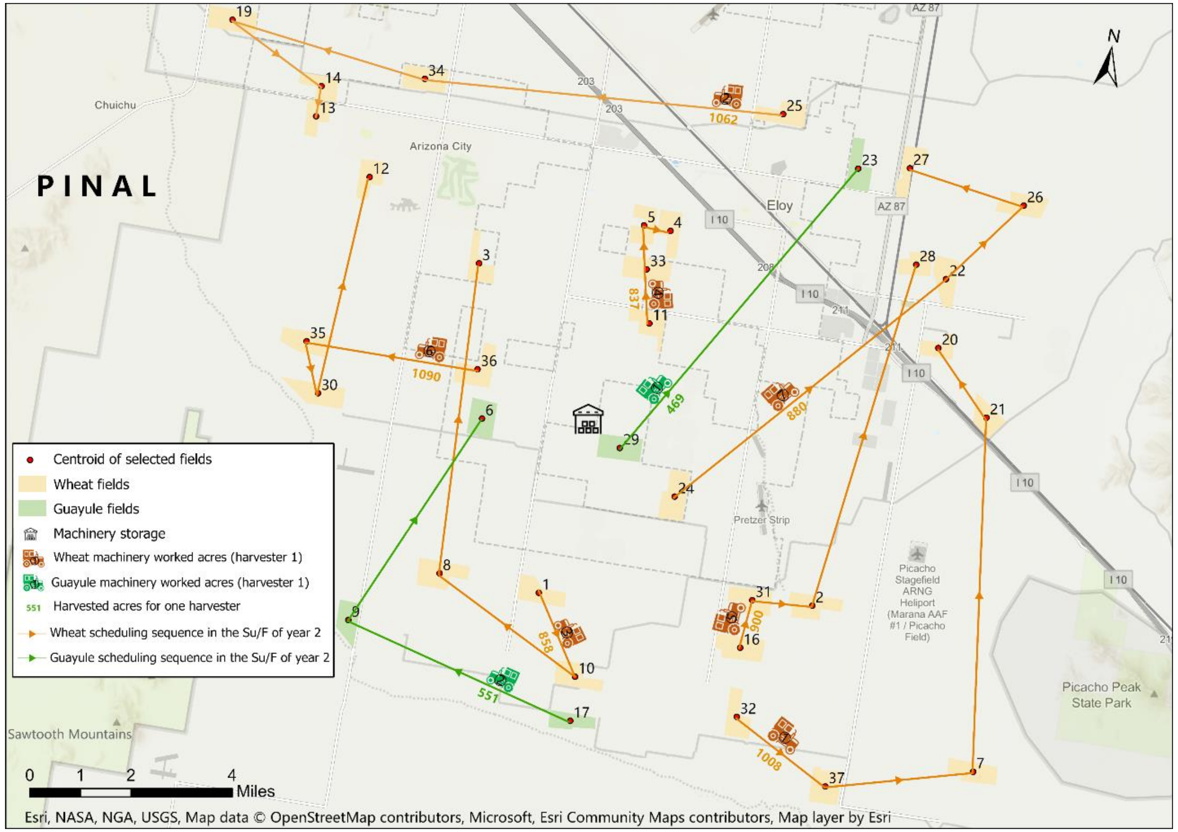


Year	Season	Acres Guayule	Acres Cotton	Acres Wheat
1	W/Sp	0	0	0
	Su/F	0	0	6949
2	W/Sp	0	6949	0
	Su/F	1020	0	6461
3	W/Sp	0	6461	0
	Su/F	487	0	6461
4	W/Sp	0	6461	0
	Su/F	1020	0	6461
5	W/Sp	0	6461	0
	Su/F	487	0	6461
6	W/Sp	0	6461	0
	Su/F	1020	0	6461
7	W/Sp	0	6461	0
	Su/F	487	0	6615
8	W/Sp	0	6615	0
	Su/F	867	0	6453
9	W/Sp	0	6453	0
	Su/F	649	0	6453
10	W/Sp	0	6453	0
	Su/F	867	0	6453

Seasons: Winter (W), Spring (Sp), Fall (F), and Summer (Su) — Guayule harvesting seasons; Cotton harvesting seasons; Wheat harvesting seasons

Guayule, cotton and wheat growing and harvesting seasons

Machinery scheduling



Guayule, cotton and wheat harvest scheduling in the Su/F of year 2

Harvesting Results

United States Department of Agriculture
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Table 4: Guayule cost breakdown ($1000 USD)

	Year	1	2	3	4	5	6	7	8	9	10	Total Cost
Guayule Costs	Rent Cost	0.00	50.00	25.00	50.00	25.00	50.00	25.00	25.00	25.00	25.00	300.00
	Operational Cost	0.00	13.37	6.39	13.37	6.39	13.37	6.39	11.36	8.50	11.36	90.47
	Transportation Cost	0.00	0.16	0.12	0.16	0.12	0.16	0.12	0.24	0.20	0.24	1.49
	Penalty Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.21	0.00	18.21	36.43
	Total Cost	0.00	63.52	31.50	63.52	31.50	63.52	31.50	54.81	33.70	54.81	428.39

Cost of change curves

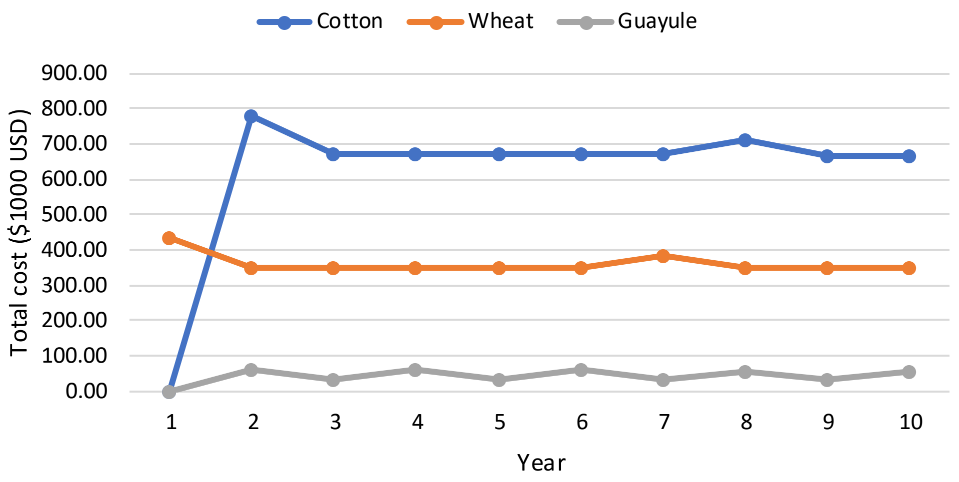
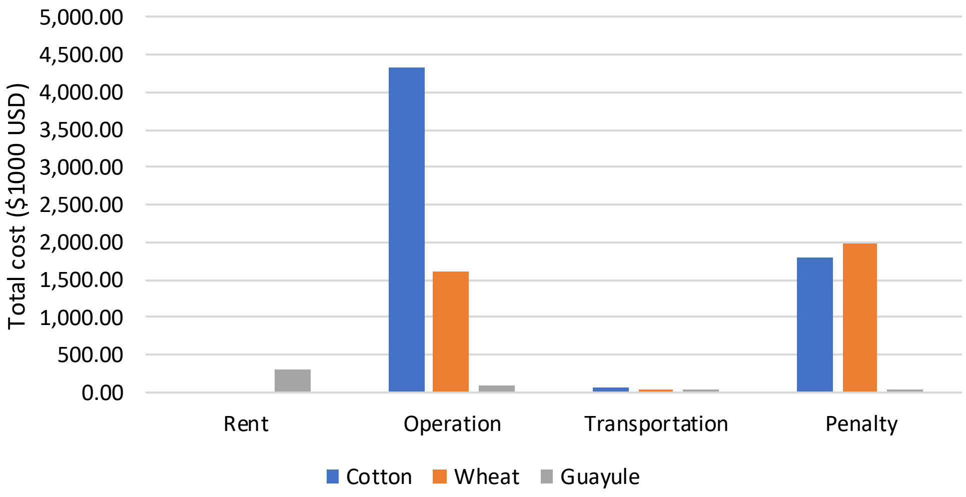


Table 5: Cotton and wheat cost breakdown ($1000 USD)

	Year	1	2	3	4	5	6	7	8	9	10	Total Cost
Cotton Costs	Rent Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Operational Cost	0.00	510.74	474.92	474.92	474.92	474.92	474.92	486.17	474.30	474.30	4,320.10
	Transportation Cost	0.00	5.61	5.45	5.45	5.45	5.45	5.45	4.90	4.75	4.75	47.25
	Penalty Cost	0.00	263.37	189.24	189.24	189.24	189.24	189.24	221.17	185.96	185.96	1,802.65
	Total Cost	0.00	779.73	669.60	669.60	669.60	669.60	669.60	712.24	665.01	665.01	6,170.00
Wheat Costs	Rent Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Operational Cost	170.25	158.31	158.31	158.31	158.31	158.31	162.06	158.10	158.10	158.10	1598.13
	Transportation Cost	3.06	2.97	2.97	2.97	2.97	2.97	2.67	2.59	2.59	2.59	28.36
	Penalty Cost	263.37	189.24	189.24	189.24	189.24	189.24	221.17	185.96	185.96	185.96	1988.61
	Total Cost	436.68	350.52	350.52	350.52	350.52	350.52	385.90	346.65	346.65	346.65	3615.11

Total cost breakdown

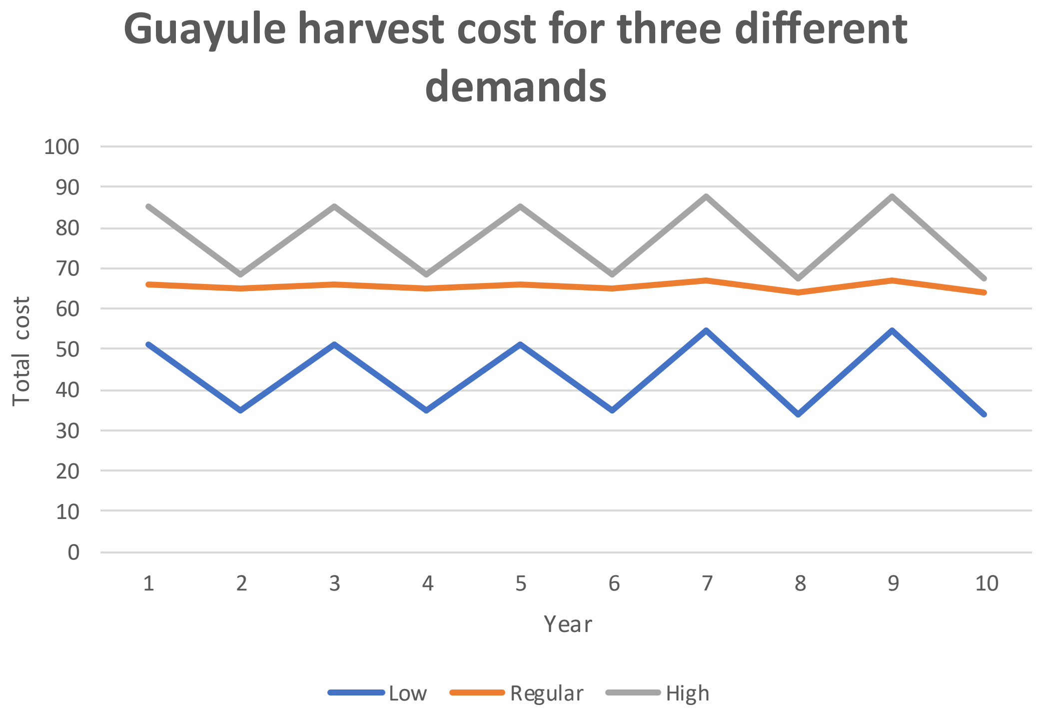


Sensitivity Analysis on Harvest Demand

- The farm yield of guayule is **12.14** ton/acre.
- The total min (max) capacity of processing facility is **500,000 (521,429)** ton/year in Maricopa and Pinal counties.
- Consider three different demands: low, regular and high demand

Table 9 Guayule harvesting cost breakdown for three different demands ($1000 USD)

Year		1	2	3	4	5	6	7	8	9	10	Total Cost
Low Demand (7,800 ton)	Rent Cost	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	250.00
	Operational Cost	10.10	9.65	10.10	9.65	10.10	9.65	11.36	8.50	11.36	8.50	98.98
	Transportation Cost	0.16	0.12	0.16	0.12	0.16	0.12	0.24	0.20	0.24	0.20	1.69
	Penalty Cost	16.15	0.00	16.15	0.00	16.15	0.00	18.21	0.00	18.21	0.00	84.87
	Total Cost	51.41	34.77	51.41	34.77	51.41	34.77	54.81	33.70	54.81	33.70	435.53
Regular Demand (11,800 ton)	Rent Cost	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	500.00
	Operational Cost	15.72	15.03	15.72	15.03	15.72	15.03	16.81	13.89	16.81	13.89	153.67
	Transportation Cost	0.24	0.19	0.24	0.19	0.26	0.19	0.27	0.31	0.27	0.31	2.49
	Penalty Cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total Cost	65.96	65.22	65.96	65.22	65.98	65.22	67.08	64.20	67.08	64.20	656.16
High Demand (15,800 ton)	Rent Cost	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	500.00
	Operational Cost	18.58	18.27	18.58	18.27	18.58	18.27	19.69	17.16	19.69	17.16	184.22
	Transportation Cost	0.31	0.20	0.31	0.20	0.31	0.20	0.30	0.31	0.29	0.31	2.77
	Penalty Cost	16.15	0.00	16.15	0.00	16.15	0.00	17.86	0.00	17.86	0.00	84.15
	Total Cost	85.04	68.47	85.04	68.47	85.04	68.47	87.85	67.47	87.84	67.47	771.15



Summary

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National Institute of Food and Agriculture

Biomass Supply Chains for Guayule and Guar

- **Module I – Facility Location and Transportation**
  - Design a stochastic model to make optimal decisions for facility locations and transportations
  - Integrates economic benefits, environmental impacts, and social impacts into the optimal design
  - Case studies in Texas and Arizona (semi-arid farms)
- **Module II – Production Planning and Machinery Scheduling**
  - Consider multi-crop planning, multi-machinery scheduling, and crop rotation
  - Determine the optimal production plans for crop rotations and machinery schedules for equipment
  - Cost and profit analysis for farmers
- **Module III – Harvest Planning and Scheduling**
  - Build an MILO model focusing on three problems: When? How? How much?
  - Obtain a 10-year harvest plan for three crops
  - Sensitivity analysis on harvest demand

Publications:

- Sun, O., & Fan, N. (2020). A review on optimization methods for biomass supply chain: models and algorithms, sustainable issues, challenges and opportunities. *Process Integration and Optimization for Sustainability*, 4, 203-226. doi:10.1007/s41660-020-00108-9
- Sproul, E., Summers, H., Seavert, C., Robbs, J., Khanal, S., Mealing, V., Landies, A., Fan, N., Sun, O., & Quinn, J. (2020). Integrated techno-economic and environmental analysis of guayule rubber production. *Journal of Cleaner Production*, 273, 122811. doi:10.1016/j.jclepro.2020.122811
- Summers, H., Sproul, E., Seavert, C., Angadi, S., Robbs, J., Khanal, S., Gutierrez, P., Teegerstrom, T., Zuniga Vazquez, D., Fan, N., & Quinn, J. (2021). Economic and environmental analyses of incorporating guar into the American southwest. *Agricultural Systems*, 191, 103146. doi:10.1016/j.agsy.2021.103146
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- Zuniga Vazquez, D., Fan, N., Teegerstrom, T., Seavert, C., Summers, H., Sproul, E., & Quinn, J. (2021). Optimal Production Planning and Machinery Scheduling for Semi-Arid Farms, *Computers and Electronics in Agriculture*, 187, 106288. DOI: 10.1016/j.compag.2021.106288.
- S. Yao, N. Fan, Clark Seavert, Trent Teegerstrom (2023) Demand-driven harvest planning and machinery scheduling for guayule, *Operations Research Forum*, 4(9): 1-25, 2023. DOI: 10.1007/s43069-022-00192-2.
- D. A. Zuniga Vazquez, N. Fan, T. Teegerstrom, C. Seavert, H.M. Summers, E. Sproul, and J.C. Quinn (2023). Optimal Design of Guayule and Guar Supply Chains for the American Southwest, *Proceedings of the IISE Annual Conference & Expo 2023*, K. Babski-Reeves, B. Eksioglu, D. Hampton, eds., 5/2023.

SBAR

USDA United States Department of Agriculture National Institute of Food and Agriculture

Ongoing research

- Incorporate the drought scenarios into planting and harvesting planning
  - M. Mahdavimanshadi, S. Yao, N. Fan, Optimal guayule harvest planning and machinery scheduling under drought scenarios in semi-arid farms, *Smart Agricultural Technology*, Vol. 7, 100420, DOI: 10.1016/j.atech.2024.100420, 2024.
  - M. Mahdavimanshadi, N. Fan, Multistage stochastic optimization for semi-arid farm crop rotation and water irrigation scheduling under drought scenarios, *Journal of Agricultural, Biological and Environmental Statistics*, 30, 310-333, DOI: 10.1007/s13253-024-00651-9, 2025.
  - M. Mahdavimanshadi, N. Fan, Crop yield prediction for semi-arid regions, *Proceedings of the IISE Annual Conference & Expo 2025*, E. Gentry, F. Ju, X. Liu, eds., 6/2025.


QUESTIONS