Stochastic Optimization of Switchgrass-based Biofuel Supply Chain Considering Feedstock Yield Uncertainty and Risk Preference

Bijay P. Sharma, Graduate Student bsharma3@vols.utk.edu

T. Edward Yu, Associate Professor tyu1@utk.edu

Burton C. English, Professor benglish@utk.edu

James A. Larson, Professor jlarson2@utk.edu

Christopher N. Boyer, Assistant Professor cboyer3@utk.edu

Department of Agricultural and Resource Economics, University of Tennessee

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Bijay P. Sharma, T. Edward Yu[1], Burton C. English, James A. Larson, and Christopher N. Boyer

Department of Agricultural & Resource Economics, University of Tennessee

INTRODUCTION

- Biofuel produced from switchgrass is potentially a socio-economically sustainable renewable energy source.
- However, feedstock yield uncertainty and high production costs are significant barriers to invest in a feedstock supply chain for biofuel production.
- Stochastic supply chain designs have primarily focused on optimizing expected economic performance based on the assumption of risk neutrality.
- Design of a risk efficient supply chain that considers biomass yield uncertainty is key to the commercialization of biofuel industry.

OBJECTIVES

Design a risk efficient switchgrass-based biofuel supply chain for large scale biofuel production under biomass supply uncertainty. Specifically, this study:

- Developed the optimal supply chain incorporating strategic land use decisions based on yield uncertainty and risk preferences of decision makers.
- Estimated the impact of USDA's Biomass Crop Assistance Program (BCAP) on designing a risk efficient supply chain under different risk preferences.

ANALYTICAL METHODS

- When supply chain design decisions are made before the realization of uncertain parameters, a ***two-stage stochastic model*** is often employed.
- First-stage (strategic/investment) decisions have to be made before the realization of uncertain parameters, whereas the second-stage (operational) decisions are allowed to have recourse.

Expected cost minimization (Model 1): Risk-neutral preference

- Computation of optimal strategic and operational level variables is driven by the minimization of the first-stage cost ($Cost_{1st\_stage}$) and the expected second-stage random costs ($Cost_{2nd\_stage}(s)$) with the probability associated with each random feedstock yield scenario ($prob\ (s)$).

$$Min:\ E(Cost) = \sum_{s \in S} Cost(s) \times prob\ (s)$$

$$Cost(s) = Cost_{1st\_stage} + Cost_{2nd\_stage}(s)$$

$$Cost_{1st\_stage} = C_{inv}^{fac} + C_{est}^{swi} + C_{opc}^{swi}$$

$$Cost_{2nd\_stage}(s) = C_{pro}^{swi}(s) + C_{stg}^{swi}(s) + C_{trans}^{swi}(s) + C_{conv}^{bio}(s) + C_{trans}^{bio}(s)$$

- Scenario independent first-stage costs include annualized costs of conversion facility investment (C_{inv}^{fac}), switchgrass establishment (C_{est}^{swi}), and opportunity cost of switchgrass (C_{opc}^{swi}).
- Scenario dependent second-stage costs include costs of switchgrass production: $C_{pro}^{swi}(s)$, switchgrass storage: $C_{stg}^{swi}(s)$, switchgrass transportation: $C_{trans}^{swi}(s)$, biofuel conversion: $C_{conv}^{bio}(s)$, and biofuel transportation: $C_{trans}^{bio}(s)$.

ANALYTICAL METHODS (Cont'd)

Conditional Value-at-Risk minimization (Model 2): Risk-averse preference

Within a given confidence interval *z*, Value-at-Risk (VaR_z) of random costs is defined as the lowest value *t* such that with probability *z* the cost will not be greater than *t* (Rockafellar and Uryasev 2000). Conditional Value-at-Risk ($CVaR_z$) is the conditional expectation of the cost above the value *t*.

$$Min: CVaR_z(Cost, z) = \frac{\sum_{s \in S} \emptyset(s) \times prob(s)}{1 - z} + VaR_z(Cost)$$

Subject to:

$$\emptyset(s) \geq Cost(s) - VaR_z(Cost), \emptyset(s) \geq 0, VaR_z(Cost) \geq 0$$

Modeling influence of BCAP subsidies

Introduced subsidy for feedstock establishment and maintenance costs offered in the BCAP.

KEY DATA AND PARAMETERS

- Spatial data in 5 square-mile for switchgrass production and biorefinery location was used for West Tennessee (Yu et al. 2016).
- Annual demand of 290 million gallons biofuel from blending facility near Memphis.
- Penalty for not fulfilling demand equals \$5/gallon and the risk aversion parameter z equals 95th percentile.
- Fifteen yield scenarios were generated from mature switchgrass yield at west Tennessee in 2006-2011 (Boyer et al. 2013) (Table 1).
- Within each scenario, normally distributed yield pattern is mapped following Jager et al. (2010).

Table 1. Simulated Yield Scenarios

Scenario	Yield (ton/acre)	Prob.
S1	0.9 ≤ δ* < 1.89	0.005
S2	1.89 ≤ δ < 2.88	0.016
S3	2.88 ≤ δ < 3.88	0.067
S4	3.88 ≤ δ < 4.87	0.124
S5	4.87 ≤ δ < 5.86	0.159
S6	5.86 ≤ δ < 6.85	0.220
S7	6.85 ≤ δ < 7.84	0.183
S8	7.84 ≤ δ < 8.84	0.118
S9	8.84 ≤ δ < 9.83	0.063
S10	9.83 ≤ δ < 10.8	0.023
S11	10.8 ≤ δ < 11.8	0.009
S12	11.8 ≤ δ < 12.8	0.007
S13	12.8 ≤ δ < 13.8	0.002
S14	13.8 ≤ δ < 14.8	0.002
S15	14.8 ≤ δ ≤ 15.8	0.002

*Denotes spatial yield

RESULTS

Decisions without BCAP subsidies

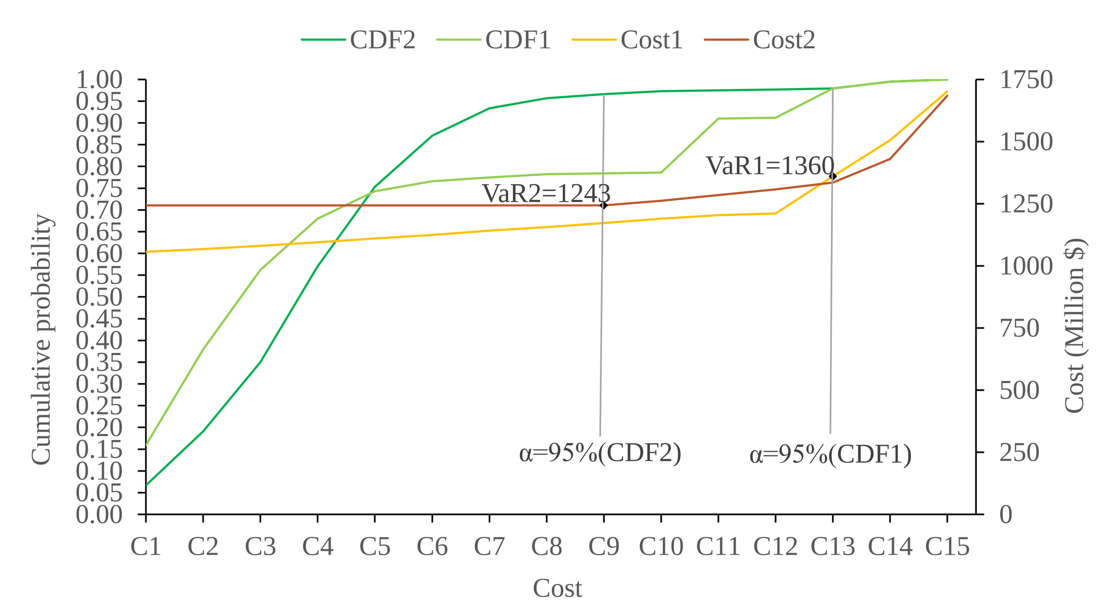

Fig. 1. CDF of optimal costs under both models

Note: Cost1 and Cost2 denotes optimal costs associated with yield scenarios for the Model 1 and 2 respectively. CDF1 and CDF2 denotes cumulative density of the optimal costs for the Model 1 and 2 respectively. Cost rank of each scenario under each model is shown in Table 2.

RESULTS (Cont'd)

Table 2. Optimal Scenario Costs

Cost*	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**
Model 1	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S4	S15	S3	S2	S1
Model 2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S2	S1

*Ranked in the ascending order

Table 3. Optimal Objective Values

Objective	Unit	Model 1	Model 2
E(Cost)	Million \$	1,124	1,249
CVaR(Cost)	Million \$	1,441	1,358

- Although expected cost increased in Model 2, risk of high costs has been minimized i.e. CVaR decreases by \$83 M (Table 3).
- Similarly, risk corresponding to 95th percentile of cost distribution has been reduced significantly in Model 2 i.e. VaR decreases by \$117 M (Fig 1).
- Probability of those high costs was effectively reduced in Model 2 (Fig 1) .
- Low opportunity cost pasture land was primarily selected without BCAP subsidies. Only crop land near the biorefineries was converted (Figs 2 and 3).
- Model 2 selected more acreages under both the pasture and crop lands to reduce high costs of low yield scenarios in Model 1.
- The color in the spit is either supplying from pasture or pasture/cropland.
- Reduction of biofuel shortage in Model 2 lowered costs of low yield scenarios (Fig 4).

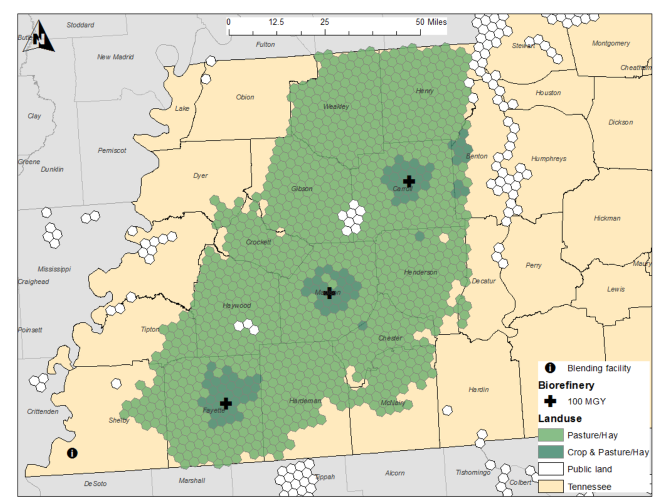

Fig. 2. Model 1 without BCAP

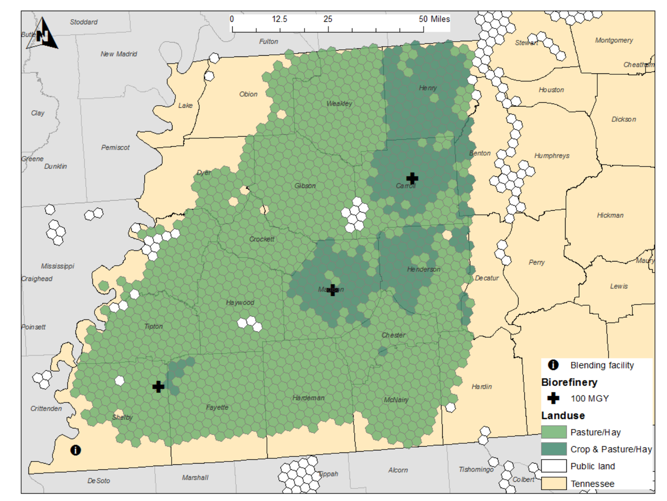

Fig. 3. Model 2 without BCAP

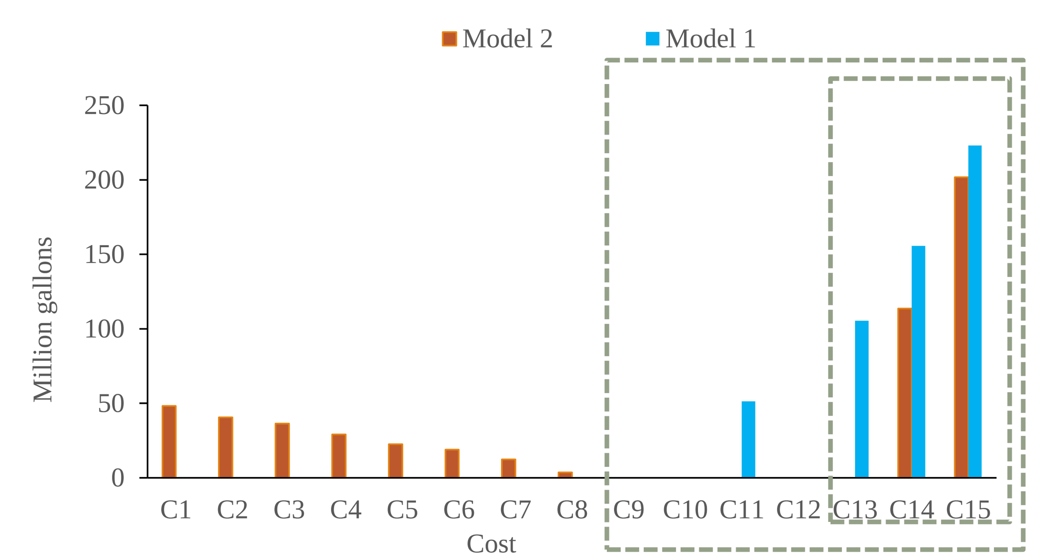

Fig. 4. Optimal scenario costs and biofuel shortage

Note: Small and large insets capture 95th percentile and above cost distribution for Model 1 and 2 respectively

RESULTS (Cont'd)

Decisions with BCAP subsidies

- With BCAP subsidies, both E(Cost) and CVaR(Cost) reduced but Model 2 achieved larger reduction because of more acreage selection (Fig. 5).

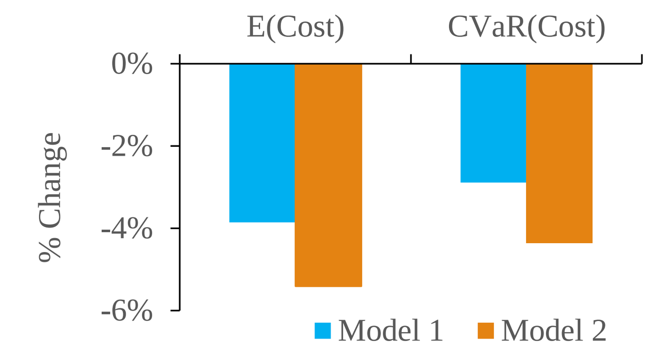

Fig. 5. Changes in objectives with BCAP

- Biorefinery locations shifted with increased crop acreage and less pasture acreage (Figs 6 and 7).
- A greater reduction in opportunity costs due to payments from BCAP for crop lands induced increased crop acreage selection.
- However, changes in land use was higher for Model 2 (Figs 3 and 7) than Model 1 (Figs 2 and 6) with more land with high spatial yields being selected.

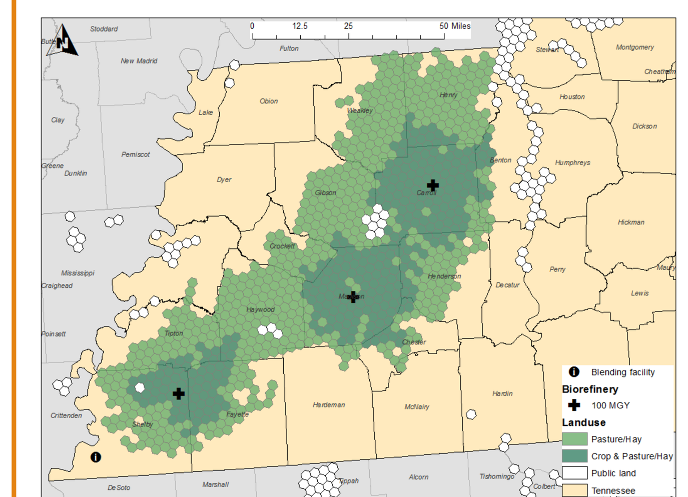

Fig. 6. Model 1 with BCAP

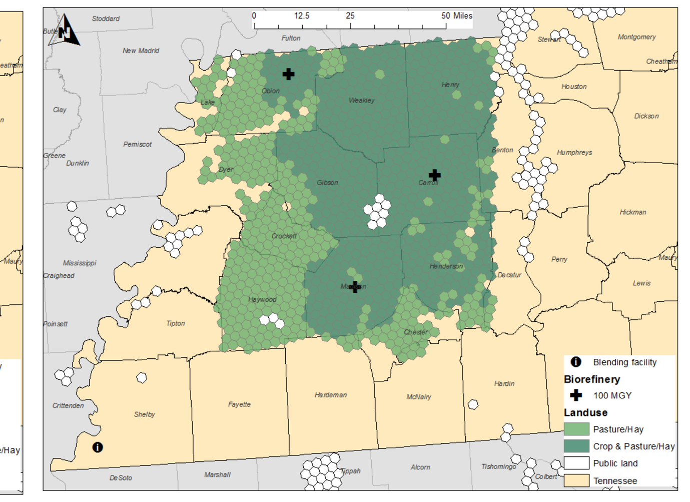

Fig. 7. Model 2 with BCAP

CONCLUSION

- More acreage was selected to reduce the cost associated with low yield scenarios in the CVaR minimization model.
- With BCAP subsidies, crop land selection increased whereas pasture land use decreased. Biomass transportation costs were also lowered.
- Optimal investment decisions i.e. feedstock acreage as well as biorefinery configuration, were more responsive to BCAP subsidies with risk-averse compared to risk-neutral decision makers under switchgrass supply uncertainty.

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[1]Corresponding author: T. Edward Yu, Agricultural & Resource Economics, University of Tennessee, tyu1@utk.edu