Welfare Analysis of Carbon Credits to the Sustainable Aviation Fuel Sector: A Game-Theoretic Perspective

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MOTIVATION

- The International Air Transport Association (IATA) has set targets of carbon neutral growth by 2020 and green-house gas (GHG) emissions reduction by 50% by 2050, compared to the level in 2005.
- Alternative technologies for lesser emissions, such as electrification, are not currently feasible in the aviation industry thus requiring Sustainable Aviation Fuels (SAF) to achieve ambitious goals on GHG emissions reduction.
- Current research on RJF deals with techno-economic or environmental analysis of potential feedstock-based conversion technologies (e.g. Diederichs et al. 2016; Bann et al. 2017).
- Economic interaction between the decision-makers supplying and processing feedstocks, along with policy supports, has not been addressed.

OBJECTIVES

- To identify the extent to which SAF from lignocellulosic feedstock can justify aviation emission reductions while addressing the economic motives of the participants.
- To determine the net welfare implications of SAF production with and without policy support in the form of carbon credits while internalizing environmental costs of aviation GHG emissions.

METHODS

- Feedstock producers (farmers) are assumed to maximize their individual profits in an attempt to fulfill the derived demand for feedstock.
- The SAF processor minimizes its costs nesting the profit maximizing behavior of the individual farmers in response to the regional SAF demand.
- A non-cooperative bi-level Stackelberg game between the feedstock producers and the processor is modeled.

Farmer i's Profit Maximization Objective

$$\underbrace{Maximize}_{\substack{\boldsymbol{x_i}=[x_{hi}]_{h\in H} \\ \boldsymbol{q_i}=[q_{ijm}]_{j\in J m\in M}}}: \ \pi_i = \sum_{j\in J}\sum_{m\in M}(p_j - \varphi_i - \theta_{ij})\, q_{ijm} - \sum_{h\in H}(\alpha + \beta_{hi})x_{hi} \qquad (1)$$

- p_j denotes feedstock price (\$/ton) offered at the processing facility *j*, φ_i denotes feedstock production cost (\$/ton) at site *i*, θ_{ij} denotes transportation cost (\$/ton) between *i* and *j*, q_{ijm} denotes feedstock supply quantity (tons) from *i* to *j* at time *m*, α denotes annualized feedstock establishment cost (\$/acre), β_{hi} denotes opportunity cost (\$/acre) for land use *h* at site *i*, and x_{hi} denotes acreage of harvested feedstock from replacing existing crop *h* at site *i*.

Processor's Cost Minimization Objective (Bi-level Optimization)

$$\underbrace{Minimize}_{\substack{\boldsymbol{p_j}=[p_j]_{j\in J} \\ \boldsymbol{z_j}=[z_j]_{j\in J}}}: \Pi = \sum_{j\in J}\sum_{m\in M}\left(p_j \sum_{i\in I} q_{ijm}\right) + \rho\sigma \sum_{j\in J}\sum_{m\in M}\left(\sum_{i\in I} q_{ijm}\right)$$

$$+ \sum_{k\in K}\left(\sum_{j\in J}\sum_{m\in M}\delta_{jk}\left(\sigma \sum_{i\in I} q_{ijm}\right)\right) + \sum_{j\in J} z_j \mu_j \qquad (2)$$

Subject to *Equation* (1)

- ρ denotes production cost (\$/gallon) for processing facility, σ denotes the feedstock-SAF conversion efficiency (gallon/ton), δ_{jk} denotes transportation cost (\$/gallon) between processing facility *j* and airport *k*, z_j denotes binary variable of processing facility establishment at *j*, and μ_j denotes amortized investment cost for processing facility *j*.

METHODS (Cont'd)

Modeling Influence of Carbon Credits

- Assuming the farmer *i* supplies feedstock only if the profit is at least r_1% greater than opportunity cost and that the processing facility *j* produces SAF only if the price-offer from the airlines is \$ r_2 greater than the break-even, net supply-chain welfare is:

$$Welfare = CS_{FS} + PS_{FS} + CS_{RJF} + PS_{RJF} - c_e E_{LCA} \qquad (3)$$

- c_e is the environmental cost of emission in \$/ton CO_2e, and E_{LCA} denotes total life-cycle assessment (LCA) based emission from SAF in ton CO_2e. PS_{FS} and PS_{RJF} are surpluses of feedstock producer and SAF processor whereas CS_{FS} and CS_{RJF} are surpluses of feedstock and SAF consumers, respectively.
- Assuming availability of processor-based carbon credit, the processor influences the optimal decisions of the farmers through its own decisions, changing the net welfare of the SAF sector.
- Total carbon credits is proportional to the GHG emission reductions achieved using SAF compared to energy-equivalent conventional jet fuel (CJF) on LCA basis.
- For the carbon credit scenarios considered, a r_3% of the total carbon credits per gallon of SAF was used as an additional margin in determining the SAF contract price.

DATA

- The optimization is driven by SAF demand assumed to be 50% of current CJF consumption (i.e. 136 million gallons) at Memphis International Airport (MEM).
- Three different carbon credit (CC) scenarios are used to evaluate the impact of potential carbon markets compared to the Baseline (no carbon credit).

Table 1. Cellulosic ATJ Conversion Parameters

ATJ product	Conversion yield	Unit
SAF	26.72	gallon/ton
Cellulosic-gasoline	5.65	gallon/ton
Cellulosic-diesel	2.93	gallon/ton
ATJ product	Conversion cost	Unit
SAF	1.89	\$/gallon
ATJ product	Conversion GHG	Unit
SAF	2.80	kgCO_2e/gallon

Table 2. RIN Credits and CC Scenarios

RIN credits		
RIN price	Unit	Level
2016-A	\$/RIN	1.85
2017-A	\$/RIN	2.69
CC scenarios		
Carbon credit	Unit	Level
CalCaT-L	\$/tonCO_2e	11.58
CalCaT-H	\$/tonCO_2e	22.85
EUETS-H	\$/tonCO_2e	42.56

Note: 2016-A and 2017-A denote RIN credits for cellulosic biofuel based on average price for 2016 and 2017, respectively. CalCaT-L, CalCaT-H and EUETS-H denote lowest carbon price in the California Cap-and-Trade program, highest carbon price in the California Cap-and-Trade program and highest carbon price in the European Union Emission Trading System, respectively.

RESULTS

Solutions of the Baseline Stackelberg Model

- The SAF processor's cost is \$1.16 billion whereas the aggregate profit of farmers is around \$16.88 million annually.
- A total of 657 thousand acres farmland is used for feedstock production including 382 thousand acres of pasture land (Fig. 1).
- More than 57% of farmers received a margin ranging from 10 to 47% over their opportunity costs of land conversion (Fig. 2).

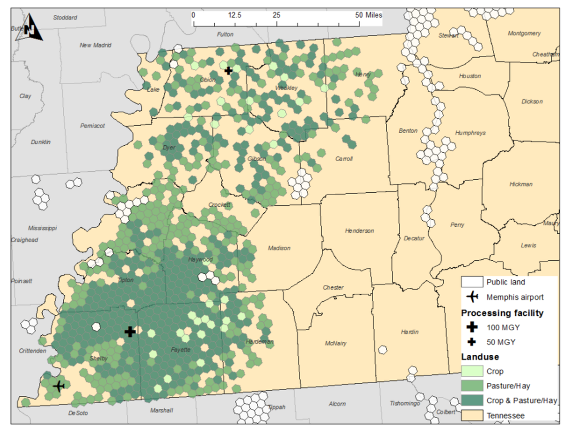

Fig. 1 Optimal land use and facility locations

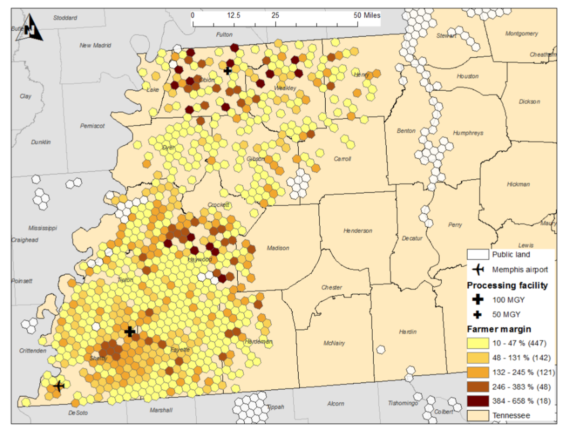

Fig. 2 Margins of feedstock suppliers
Note: Number in the parenthesis refers the amount of feedstock suppliers

- The SAF conversion has the highest GHG emissions (i.e. around 380 thousand tons of CO_2e) whereas land use change sequestered above 57 thousand tons of CO_2e GHG emissions.
- Accounting for GHG emissions, there is a net supply-chain welfare of approximately \$4.29 million for the Baseline with no surplus to the airlines.

Optimal Solutions for CC Scenarios vs Baseline

- The processor's cost decreased by \$17.65, \$32.57, and \$59.50 million for CalCaT-L, CalCaT-H, and EUETS-H scenarios, respectively, compared to Baseline.
- Total farmer profit declined by \$5.88, 5.90, and 10.45 million for CalCaT-L, CalCaT-H, and EUETS-H scenarios, respectively, compared to Baseline.
- Carbon credits provide farmers incentives to use more crop lands but less pasture lands for switchgrass production (Fig. 3).
- Land use change sequestered 31 to 47 thousand tons more of CO_2e GHG emissions for CC scenarios compared to Baseline.

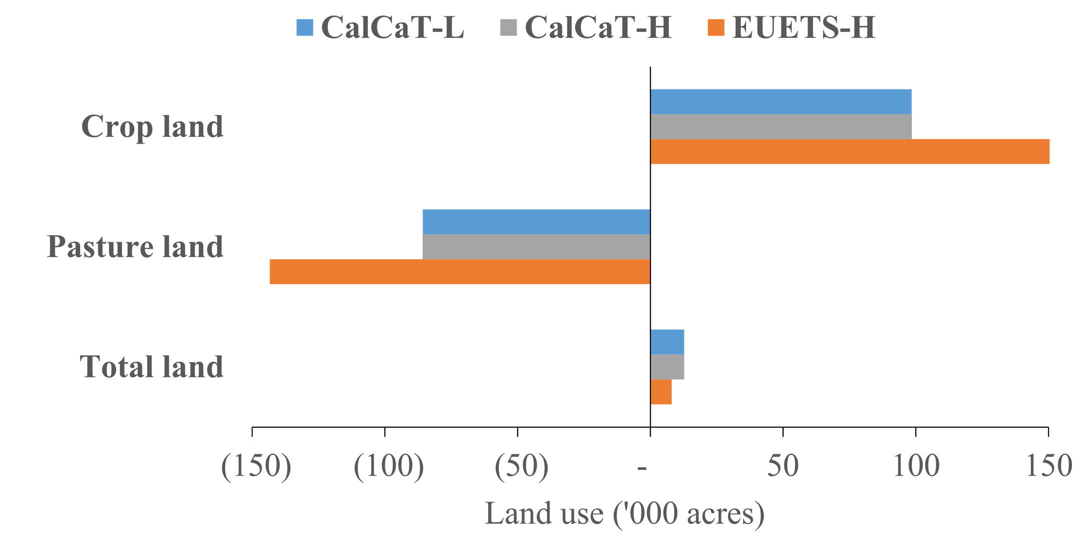

Fig. 3 Difference in land use for CC scenarios against Baseline

RESULTS (Cont'd)

- Airlines' surpluses increased by \$16.12, \$29.55, and \$53.79 million for the CalCaT-L, CalCaT-H, and EUETS-H scenarios, respectively, compared to the Baseline (Fig. 4).
- The net supply-chain welfare increased by \$12.71, \$27.61, and \$50.62 million for the CalCaT-L, CalCaT-H, and EUETS-H scenarios, respectively, compared to the Baseline (Fig. 4).

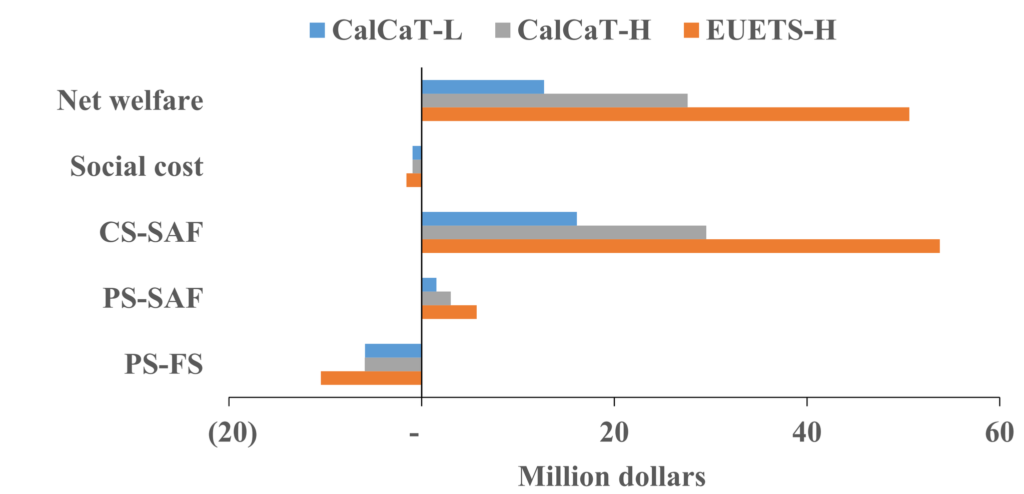

Fig. 4 Difference in welfare for CC scenarios against Baseline

Note: PS-FS and PS-SAF denote surplus for feedstock producer, surplus for SAF producer, and surplus for SAF consumer, respectively.

Economic Feasibility and GHG Emission Abatement Cost

- The total LCA-based GHG emissions reduction through displacement of the fossil fuels with the SAF products is 62.5% to 65% .
- With the 2016-A RIN credit, the implicit subsidy from airlines is \$1.89 to \$1.49/gallon, equivalent to abatement costs of \$198 to \$151/ton CO_2e.

CONCLUSIONS

- Carbon credit induced farmers to convert more crop lands with high opportunity costs into feedstock production, resulting in lower farmers' surplus.
- However, carbon credit led a net welfare gain to the SAF sector, primarily due to increment in the airlines' surplus (equivalently, reduction in the processor's cost).
- The SAF and its co-products achieved a 62.5% LCA-based GHG emissions reduction. The GHG emissions reduction increased to 65% with carbon credit through displacement of the CJF and fossil fuels.
- Thus, carbon credit had positive influence on aviation GHG emissions reduction, and net welfare of SAF sector. However, RIN credits heavily influenced the economic feasibility of SAF.

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