IOWA STATE UNIVERSITY
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A game theory analysis of market incentives for US switchgrass ethanol

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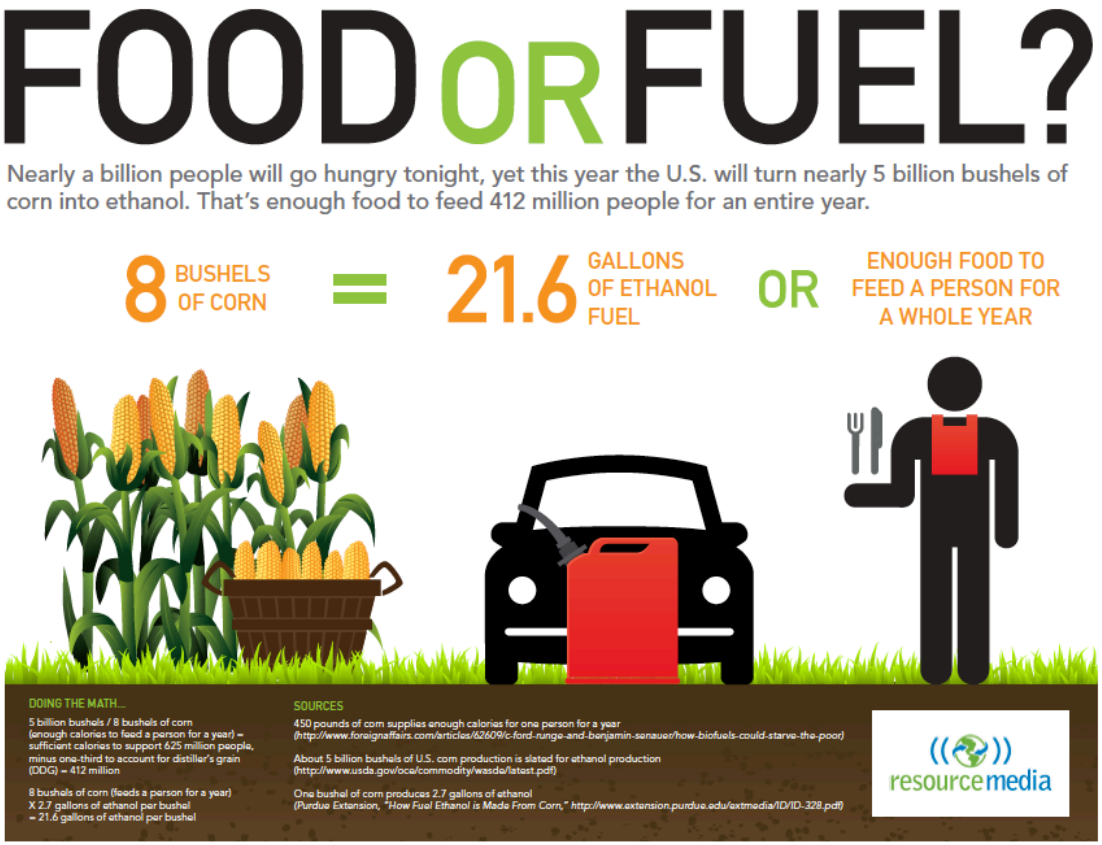
Luo, Yi, and Shelie Miller. "A game theory analysis of market incentives for US switchgrass ethanol." *Ecological Economics* 93 (2013): 42-56.

Introduction: Biofuel & Cellulosic Biofuel

- Renewable Fuel Standard (RFS): 46 billion gallons biofuel produced in 2022, 21 billion gallons of which is cellulosic biofuel.

Introduction: Biofuel & Cellulosic Biofuel

- "Nearly a billion people will go hungry tonight, yet this year the U.S. will turn nearly 5 billion bushels of corn into ethanol. That's enough food to feed 412 million people for an entire year."



Introduction: Biofuel & Cellulosic Biofuel

- Cellulosic ethanol

  --Switchgrass

  --Miscanthus

  --Corn stover

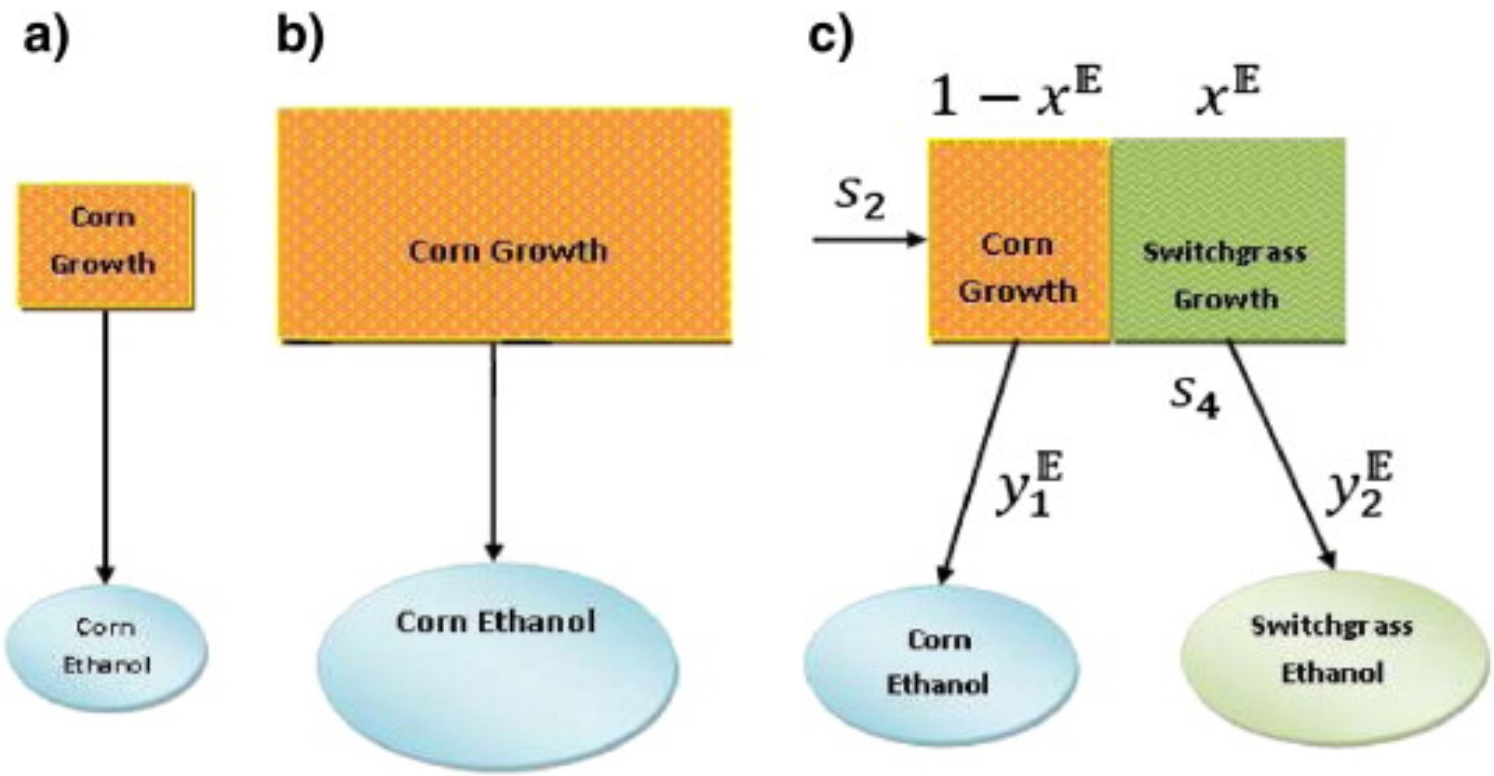
  ……

- Switchgrass is widely recognized as a leading crop for ethanol production

Introduction: Summary

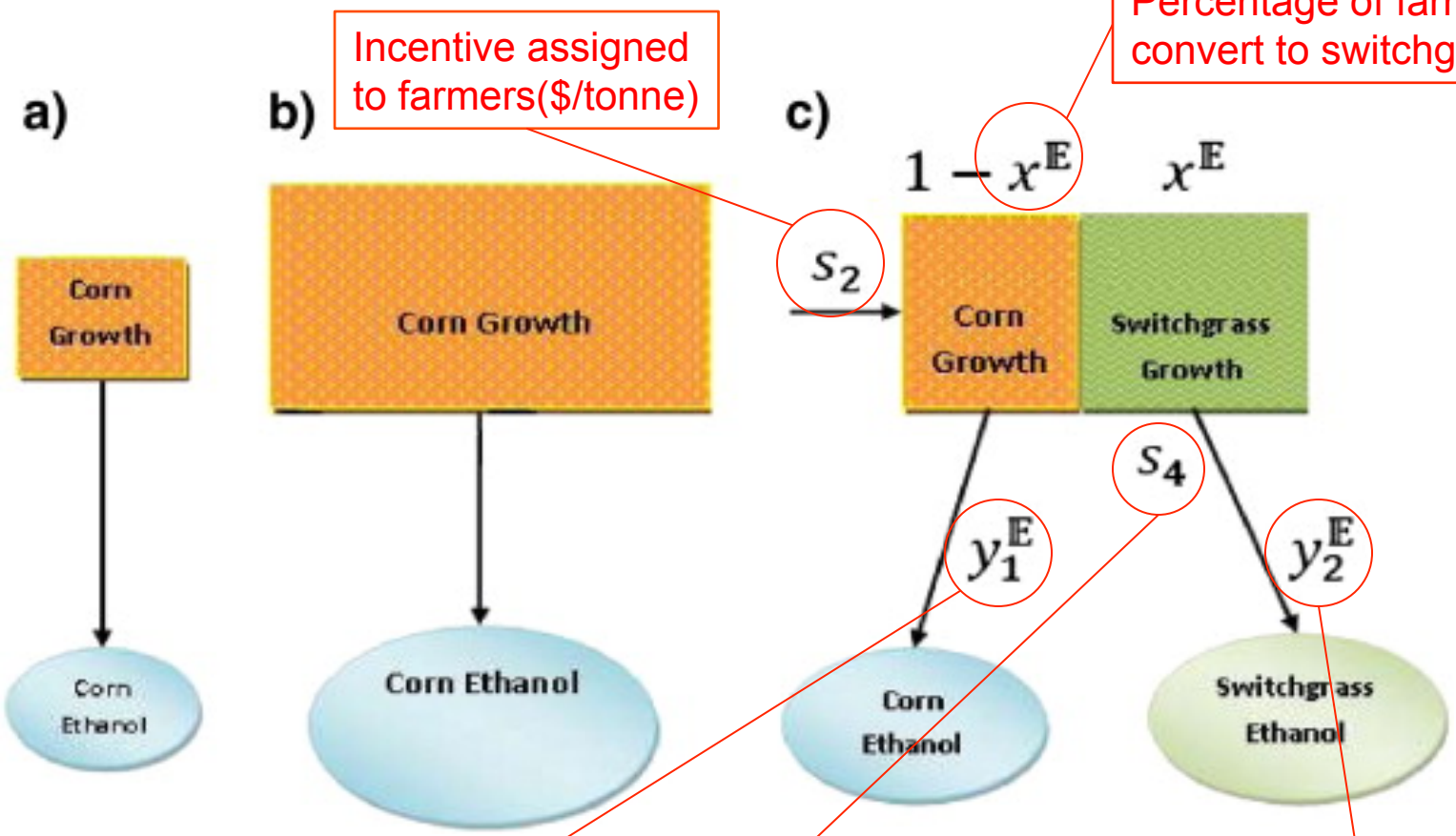
- This paper analyzed and modeled the biofuel supply chain to understand the drivers of switchgrass growth and cellulosic ethanol production.
- The model provides a framework to explore market and technical conditions that may affect potential cellulosic ethanol production, and incentive mechanisms that may be employed to stimulate the industry.

Introduction: Summary



- (a) Without monetary incentives at current time;
- (b) a “dummy case” without monetary incentives;
- (c) the realization of the RFS with the incentives in place.

Notations



Incentive assigned to farmers($/tonne)

Percentage of farmers convert to switchgrass

Percent of corn purchased by ethanol producers

Incentive assigned to ethanol producers($/liter)

Percent of switchgrass purchased by ethanol producers

Game Theory

- Decisions x^E, y^E can be estimated using game theory since all actors are assumed to behave rationally, and each individual tries to maximize their own profits.
- Superscript E indicates estimated decision from the equilibrium of the corresponding game.
- Farmers i=1,2,3,…,N

Model: Farmers' Production Decisions

- Assumed that the amount of the product uniquely determines its price *p* ($/tonne) and their relationship is linear, then we have the following price function:
- P=U-Vz
- where *U* and *V* are the maximum price ($/tonne) and the marginal price ($/tonne^2) of the good respectively

Model: Farmers' Production Decisions

- Estimated corn price($/tonne):

$$P_1 = u_1 - v_1 \sum_{i=1}^{N} (1 - x_i) M R_1,$$

Land area

Yield rate of biomass

- Switchgrass price P_2 is not modeled as a function of decision x_i in the incentive mechanism.
- Farmer i's expected payoff:

$$l_i = (P_2 - C_2 + s_2) x_i M R_2 + (P_1 - C_1)(1 - x_i) M R_1 \quad i = 1, 2, 3 \ldots N.$$

Costs of growing corn

Incentive

Yield rate of biomass

Costs of growing switchgrass

Model: Farmers' Production Decisions

- The interaction of *N* farmers in the biofuel industry is modeled as a Cournot oligopoly. Plug in the corn price and take:

$$\frac{\partial l}{\partial x} = 0$$

- Farmer's decision to grow switchgrass and corn on his/her land can be predicted as:

$$x = 1 - \frac{(C_2 - P_2 - s_2)R_2 + (u_1 - C_1)R_1}{(N+1)v_1 MR_1^2} \text{ and}$$

$$1 - x = \frac{(C_2 - P_2 - s_2)R_2 + (u_1 - C_1)R_1}{(N+1)v_1 MR_1^2},$$

Model: Biofuel Market

- Merge all xi:
- $P_1 = u_1 - v_1 N(1-x) MR_1$
- Biofuel price P_5($/liter):

$$P_5 = u_5 - v_5 \left[N x^E MR_2 y_2 R_4 + N\left(1 - x^E\right) MR_1 y_1 R_3 \right],$$

Conversion rate of switchgrass ethanol

Percentage of biomass produced by farmers that is purchased by switchgrass ethanol producers

Percentage of biomass produced by farmers that is purchased by corn ethanol producers

Conversion rate of corn ethanol

Model: Biofuel Producers' Decisions

- The expected payoffs of corn ethanol producers:

$$o_3 = y_1 N\left(1-x^{E}\right) MR_1 R_3 (P_5 - C_3) - y_1 N\left(1-x^{E}\right) MR_1 P_1$$
$$= y_1 N\left(1-x^{E}\right) MR_1 [R_3 (P_5 - C_3) - P_1],$$

- The expected payoffs of switchgrass ethanol producers:

$$o_4 = y_2 N x^{E} MR_2 R_4 (P_5 - C_4 + s_4) - y_2 N x^{E} MR_2 P_2$$
$$= y_2 N x^{E} MR_2 [R_4 (P_5 - C_4 + s_4) - P_2]$$

Model: Biofuel Producers' Decisions

- The interaction between the corn ethanol producers (leader) and the switchgrass ethanol producers (follower) is modeled as a Stackelberg game.
- Corn ethanol producers' feedstock purchase decisions:

$$y_1^B = \frac{R_4R_3u_5 + R_4R_3C_4 - R_4R_3s_4 + R_3P_2 - 2R_4R_3C_3 - 2R_4P_1}{2R_4R_3^2v_5N(1-x^B)MR_1},$$

<1

- Switchgrass ethanol producers' feedstock purchase decisions:

$$y_2^B = \frac{R_4R_3u_5 - 3R_4R_3C_4 + 3R_4R_3s_4 - 3R_3P_2 + 2R_4R_3C_3 + 2R_4P_1}{4R_4^2R_3v_5Nx^BMR_2},$$

=1 (optimal scenario)

Model: Incentives

- Target market share of cellulosic ethanol:

$$A = \frac{x^E NMR_2 y_2^E R_4}{x^E NMR_2 y_2^E R_4 + (1 - x^E) NMR_1 y_1^E R_3}.$$

- Therefore the incentives should maximize the numerator, which is obtained by the following nonlinear optimization problem

Model: Incentives

$(F\ )$ Maximize $x^{\mathbb{D}}\ n^{\mathbb{D}} MR_2 y_2^{\mathbb{D}} R_4$ s.t.

$$P_1 = u_1^{\mathbb{D}} - v_1^{\mathbb{D}}\ n^{\mathbb{D}}\left(1 - x^{\mathbb{D}}\right) MR_1$$

$$P_5 = u_5^{\mathbb{D}} - v_5^{\mathbb{D}} Q$$

$$\left(1 - x^{\mathbb{D}}\right)\left[\left(n^{\mathbb{D}} + 1\right) v_1^{\mathbb{D}} MR_1^2\right] = \left(C_2 - P_2 - s_2^{\mathbb{D}}\right) R_2 + \left(u_1^{\mathbb{D}} - C_1\right) R_1$$

$$\left(C_2 - P_2 - s_2^{\mathbb{D}}\right) R_2 + \left(u_1^{\mathbb{D}} - C_1\right) R_1 \leq \left(n^{\mathbb{D}} + 1\right) v_1^{\mathbb{D}} MR_1^2$$

$$\left(C_2 - P_2 - s_2^{\mathbb{D}}\right) R_2 + \left(u_1^{\mathbb{D}} - C_1\right) R_1 \geq 0$$

$$R_4 R_3 u_5^{\mathbb{D}} - 3R_4 R_3 C_4 + 3R_4 R_3 s_4^{\mathbb{D}} - 3R_3 P_2 + 2R_4 R_3 C_3 + 2R_4 P_1 = 4R_4^2 R_3 v_5^{\mathbb{D}} x^{\mathbb{D}}\ n^{\mathbb{D}} MR_2$$

$$R_4 R_3 u_5^{\mathbb{D}} + R_4 R_3 C_4 - R_4 R_3 s_4^{\mathbb{D}} + R_3 P_2 - 2R_4 R_3 C_3 - 2R_4 P_1 \geq 0$$

$$R_4 R_3 u_5^{\mathbb{D}} + R_4 R_3 C_4 - R_4 R_3 s_4^{\mathbb{D}} + R_3 P_2 - 2R_4 R_3 C_3 - 2R_4 P_1 \leq 2R_4 R_3^2 v_5^{\mathbb{D}}\left(1 - x^{\mathbb{D}}\right) n^{\mathbb{D}} MR_1$$

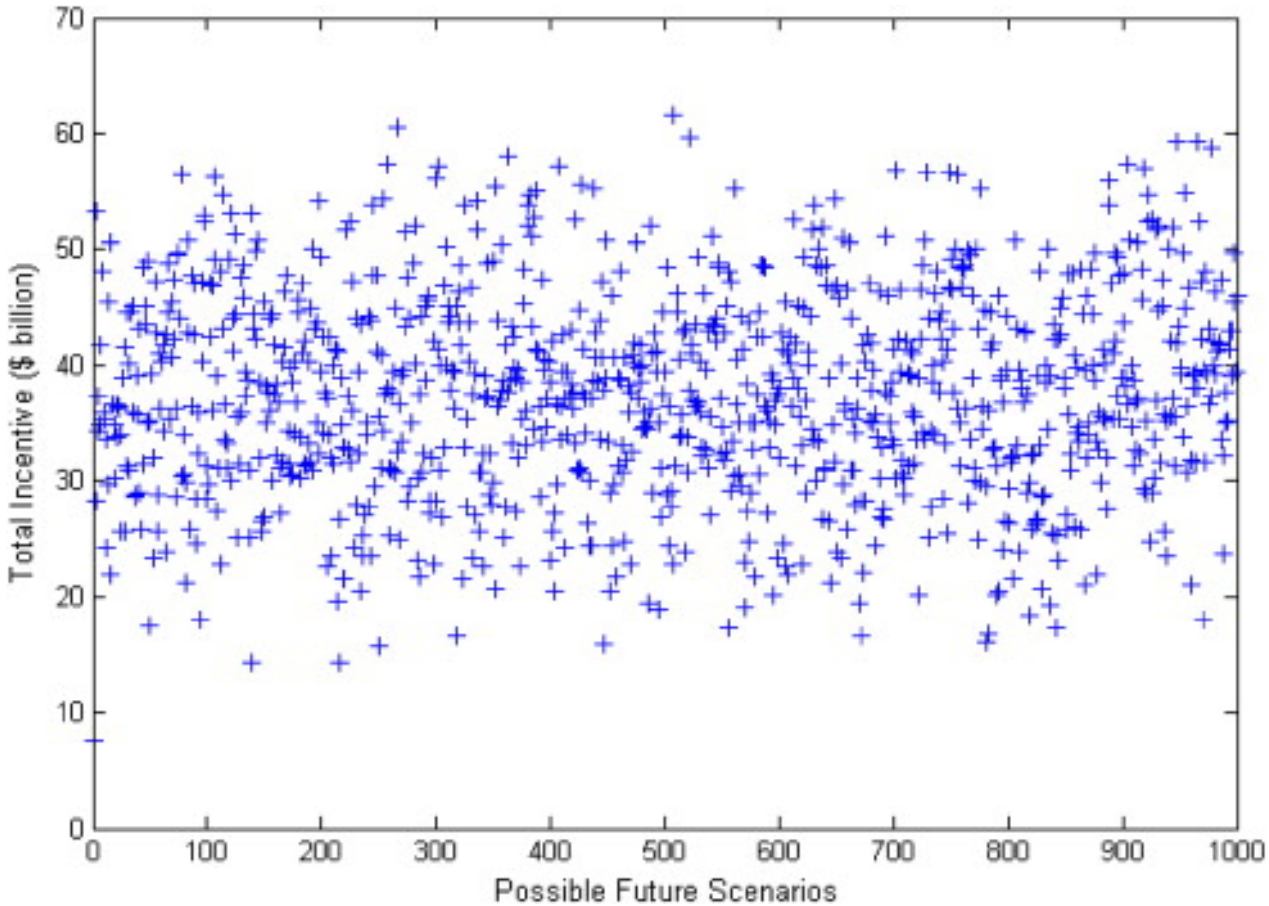
$$\left(P_2 - C_2 + s_2^{\mathbb{D}}\right) R_2 x^{\mathbb{D}} > 0$$

$$R_4\left(P_5 - C_4 + s_4^{\mathbb{D}}\right) > P_2.$$

- Solved in GAMS based on a case of 300,000 farmers.

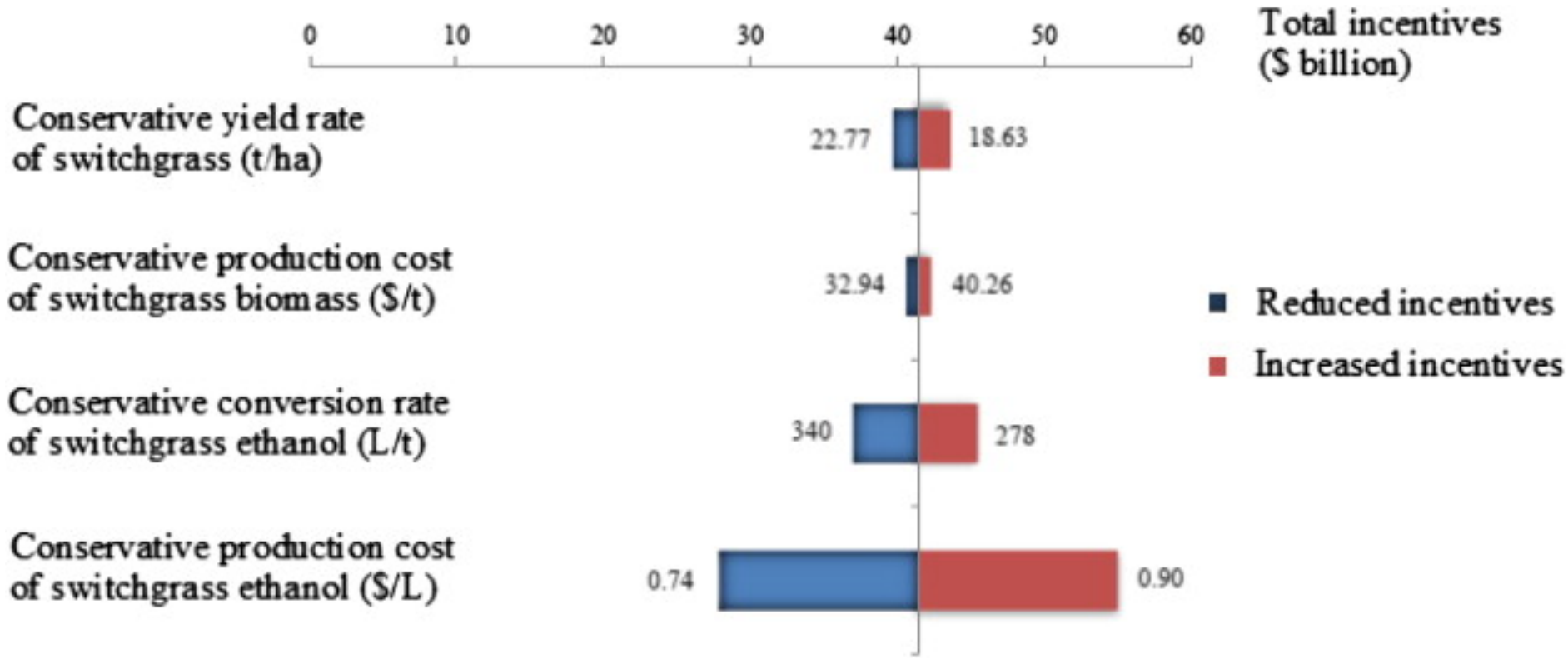
Result

- $10–60 billion in incentive as needed to reach the RFS goals



Result

- The potential incentive is sensitive to technologies.



Contribution

- This paper pointed out the difficulty of reaching RFS target. Revised Renewable Fuel Standard (RFS2) adjusted the mandate.
- The paper provided one potential commercial mechanism between farmers and biofuel producers.
- A valid practice of applying game theory to biofuel supply chain analysis.

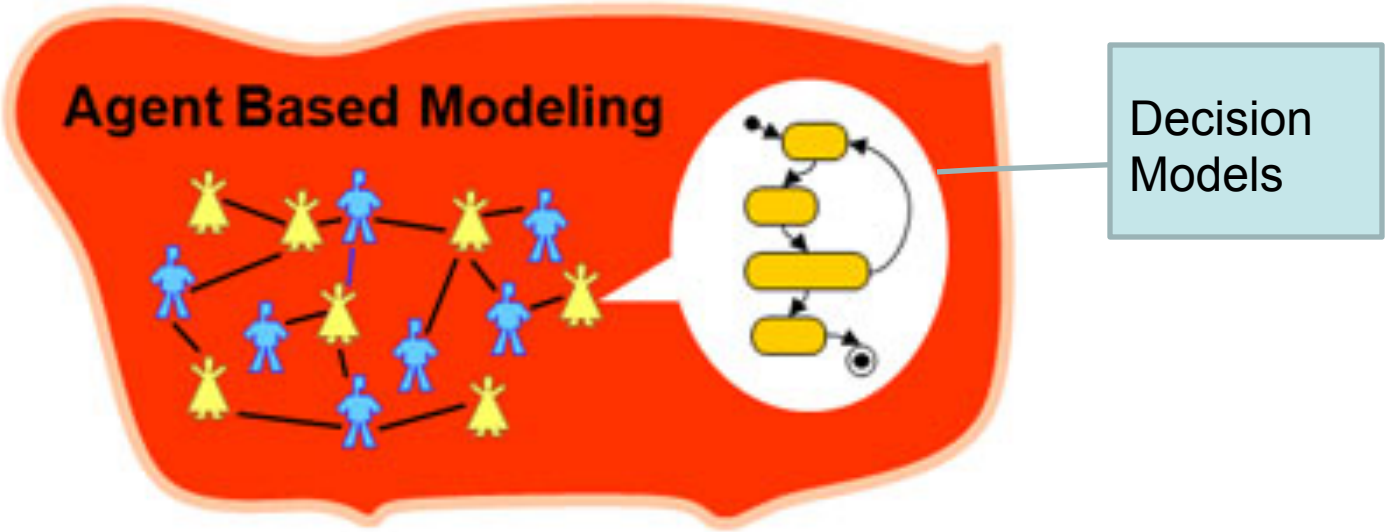
Defectives

- Rational farmers not only consider profitability, but also environmental impacts.

  --Goodness to environment is an advantage of switchgrass
- In reality business could be different.
- Nonlinear solvers cannot ensure optimality.
- Can each farmer know his impact on corn market price?

My research

- (Individual) Farmer decision making model
→ (Interacting) Bioenergy producer's model
→ Analysis and predictions
- Agent-based Modeling (ABM) and simulation



Agent-based Modeling (AnyLogic, 2015)

My research

- Producers rent lands.
- Bioenergy Producers(BP) offer contracts on bioenergy crops or biomass.
- Farmers respond to the offers.
- BP get feedback

  -- High contract prices leads to high cost

  -- Low contract prices leads to low productivity

My research: Farmers' model

Price of Bioenergy Crop

Predicted Corn Price

Predicted Corn Yield

$$\max_{x^W, x^C, t_k^W} \sum_k k t_k^W p_k^W x^W + \left(6 - \sum_k k t_k^W\right)(\overline{P^C}\,\overline{R^C} - c)x^W + 6(\overline{P^C}\,\overline{R^C} - c)x^C$$

Constant Farming Cost per Acre of Corn

$$\text{s.t.} \quad x^W + x^C \le A$$

$$\sum_k t_k^W \le 1$$

$$t_k^W \in \{0,1\}$$

$$k \in \{3,4,5,6\}$$

Acreage of Bioenergy Crop

Acreage of Corn

Binary, Decision of Contract Length

Total Land Acreage

Options of Contract Length

My research: Producers' model

- Contract price for farmer i:
- $p_i^W = a\overline{R_i^C} + bt_i^W + c + \varepsilon^i$
- $\varepsilon^i \sim N(0, \sigma)$
- a, b, c are to be determined.
- Objective function:

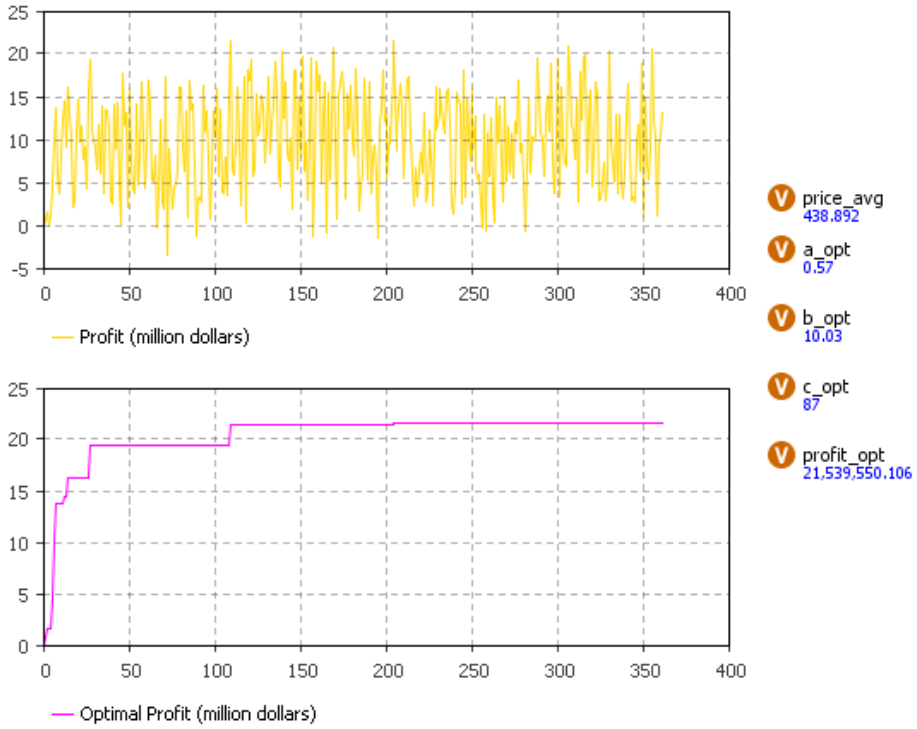
$$\max\ \alpha \sum_i g\,\overline{R_i^C} k_i^* t_{k,i}^{W*} x_i^{W*} - \sum_i p_i^{W*} k_i^* t_i^{W*} x_i^{W*}$$

My research: Solution

- Farmer's model is linearized.
- CPLEX package can be added as a dependency in AnyLogic© to write the models in.
- cplex.jar can be called repeatedly to solve models
- Agent-based simulation in AnyLogic

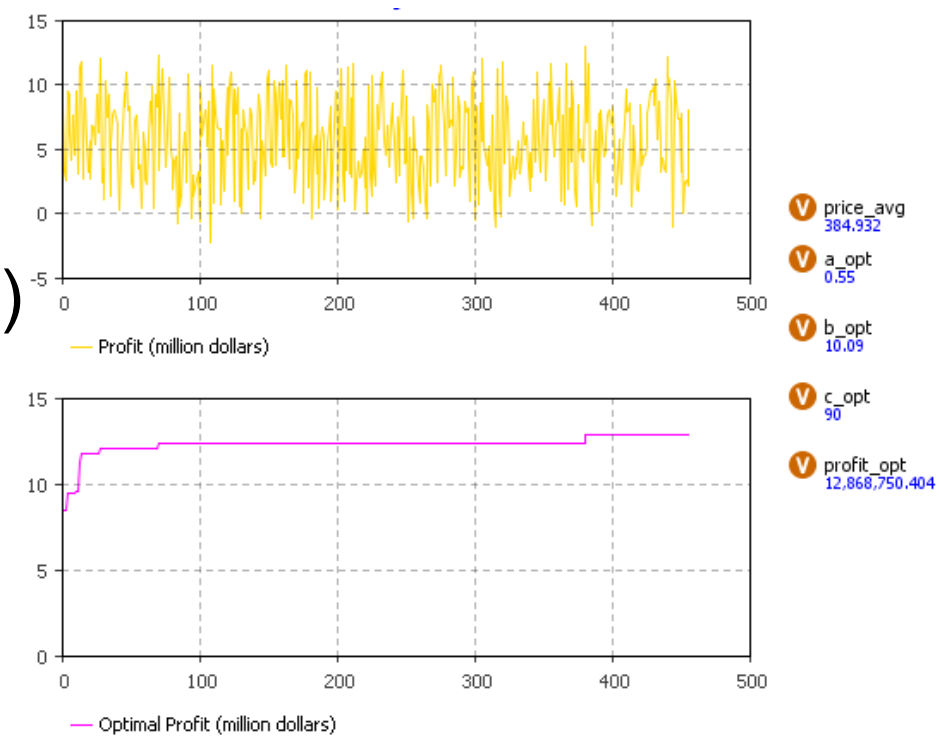
My research: Result

- Corn price = $3.25/bushel.
- Optimal profit in 6 years stable at around 21.5 million dollars.
- (a, b, c)= (0.57, 10.03, 87)
- Average contract price is around $439/acre.



My research: Interesting finding

- Corn price = $5.00/bushel.
- Optimal profit in 6 years stable at around 12.9 million dollars.
- (a, b, c)= (0.55, 10.09, 90)
- Average contract price is around $385/acre.
- Lower average contract price!



Thank you!

Questions?