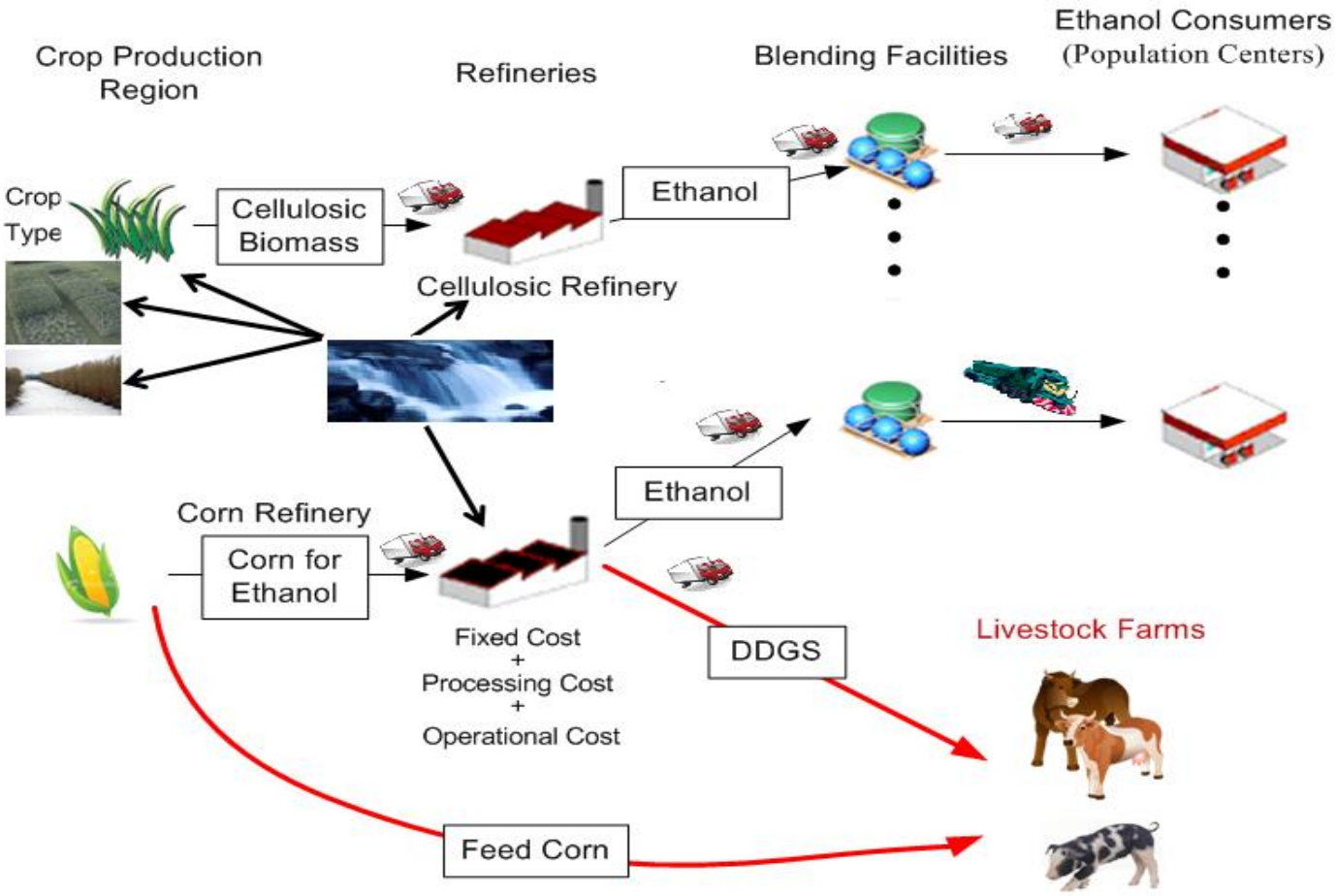
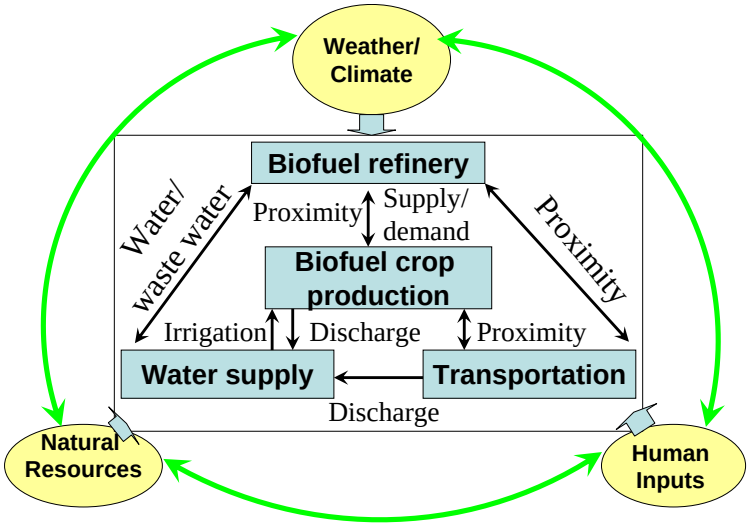
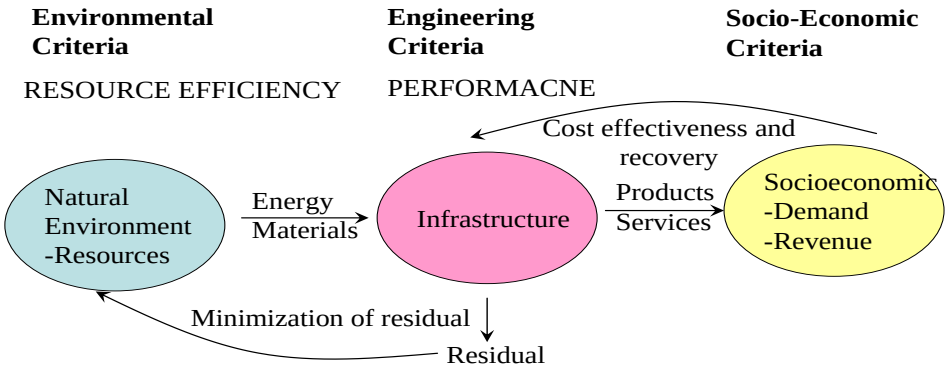
Interdependence, Resilience and Sustainability of Infrastructure Systems for Biofuel Development

PI: Ximing Cai, Co-PIs/SPs: Ouyang Yanfeng, Madhu Khanna, Atul Jain, Gregory McIsaac, Steven Eckhoff, Imad Al-Qadi, Sivapalan Murugesu, Tze Ling Ng
University of Illinois at Urbana-Champaign

Stephen Gasteyer
Michigan State University

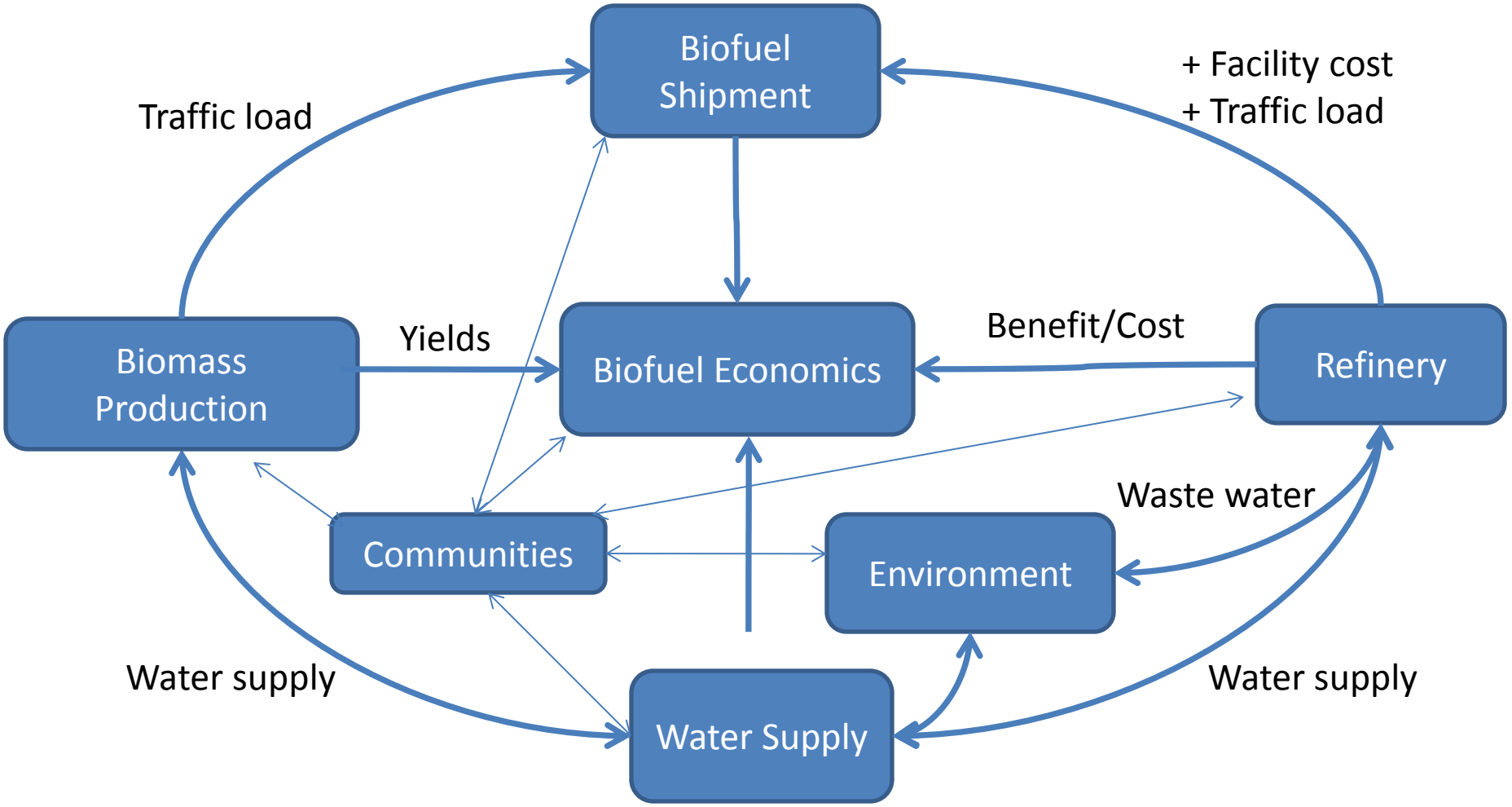




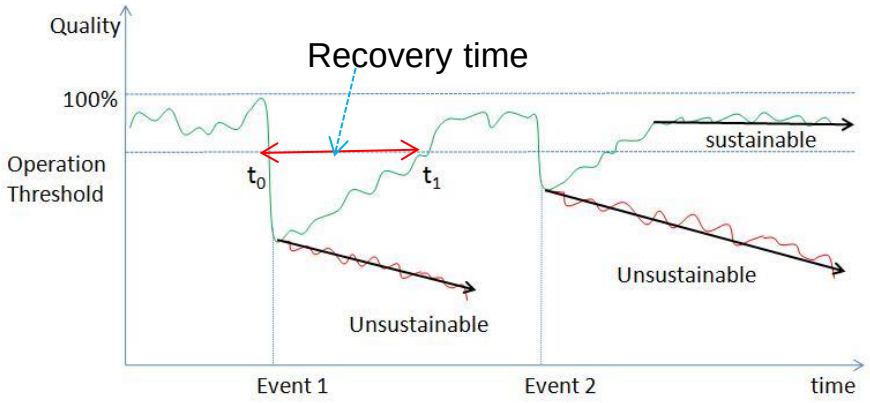


- **Interdependencies of subsystems**
  - Input/output (e.g. biofuel production transportation refineries)
  - Proximity (e.g. refineries & farms, refineries & water supply)
  - Common environmental (e.g., climate, land, water quality etc.) and social factors (community support, institutional settings)
- **Infrastructure resilience and sustainability**
  - The emerging bio-economy will increase the interdependencies among infrastructure systems and interactions among engineered infrastructures, social communities and the natural environment.
  - Physical resilience vs. social resilience
- **3-D approach to assess system sustainability**

System of Systems
(a coupled human-natural system)



A generic mathematical framework to address interdependence, resiliency and sustainability:



Resiliency & Sustainability Conceptual Development

Interdependency:

$$\mathcal{I}_{ij}(t) = \frac{\partial s_i(t+1)}{\partial s_j(t)}.$$

The dependency of subsystem ***i*** on subsystem ***j*** is defined as the change in system ***i*** resulted from one unit change in subsystem ***j***.

$$\mathcal{R}_{art} = \mathbb{E}_{j\in\mathcal{F}}[\tau_j] = \sum_{j\in\mathcal{F}} p_j\tau_j,$$

$$\mathcal{R}_{wrt} = \sup_{j\in\mathcal{F}}[\tau_j],$$

$$\tau_j = [argmin\ \tau \mid Q(t+\tau) \geq 1-\delta,\ s(t) \equiv s_j]$$

The **resiliency** of an infrastructure system is its capability to get back to its operational boundary after being affected by disruptions. Measures of resiliency include **functionality degradation**, r**ecovery time**, **recovery speed** and **adaptability**.

Sustainability:

$$\kappa = \lim_{T\to\infty} \mathbb{E}\left[\frac{1}{T}\sum_{t=0}^{T} Q(t)\right]$$

System **sustainability** is its long-term capability to use its limited resources effectively to maintain its functionality and to endure stresses.

Nguyen, Cai and Ouyang (2011), Modeling Infrastructure Interdependencies, Resiliency and Sustainability

Numerical Work: Resiliency Metrics

We deal with both long-term stress and short-term press events:

Long-term stress metrics to describe system response to trends due to environmental change and infrastructure degradation

- Adaptation in land use (e.g., new biofuel crops) and engineering development (e.g., optional transportation systems)
- Community change to adjust to new environment and technology

Short-term press metrics to describe response to extreme events: weather (flooding and drought), transportation accidents, etc.:

- Vulnerability (the worst case)
- Recover time and speed
- Propagation extent: element vs. system

Numerical Work: Sustainability Metrics

Environmental metrics:

- Flow regime
- Water quality (e.g., nitrate load to streams)
- Soil and sediment
- CO2 emissions

Engineering infrastructure metrics:

- Structure and service survivability
- Benefit/cost balance, especially the reliable financial sources for capital investment and O&M
- Bottleneck infrastructures over space and time

Socio-economic metrics:

- Biomass and biofuel productivity
- Income and social welfares
- Community development
- Policy incentives and market development

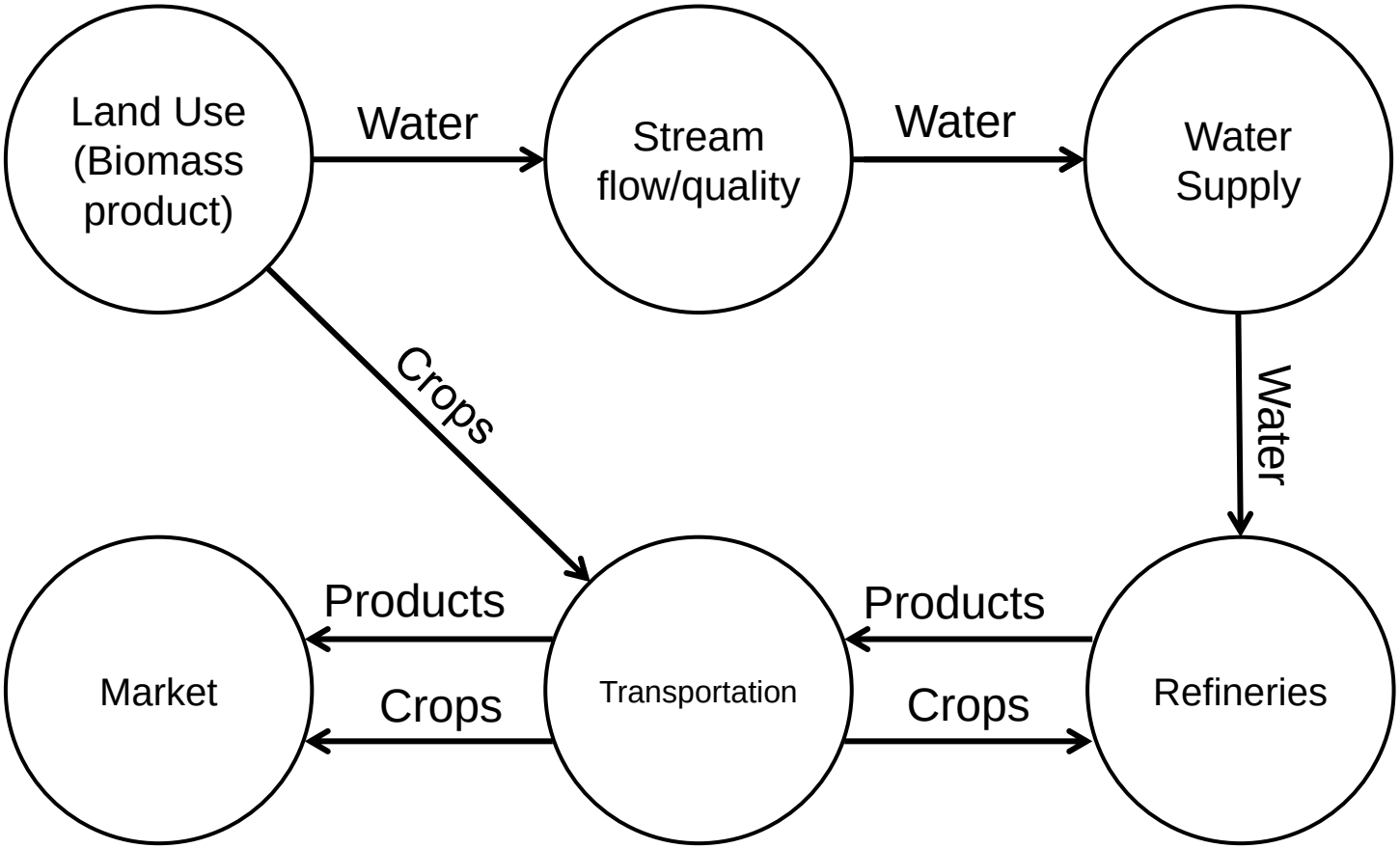
Incorporate Metrics in Modeling Analyses

- Quantify the connectedness and interdependences between the sub-systems

- Conduct the modeling analysis between the sub-systems, such as refinery and biomass production systems, transportation and market systems, water and refinery systems etc.

- Develop a model of the “system of systems”, which integrates all the essential inter-relationships into a consistent model, and compute the SRR metrics from the model outputs

Optimization Model Overview



Scope of Model

Sub-systems

Transportation
Refineries
Land use
Water quality
Water supply

Refinery types

Corn ethanol
Cellulosic ethanol

Transportation

Road
Rail

Products

Corn for food
Corn for ethanol
Soybeans for food
Corn stover
Miscanthus
Ethanol
Dried distillers grains

Water sources

Surface water
Ground water

Water users

Refineries
Towns/Cities
Farmers

Water pollutants

Nitrate
Phosphorus
Sediments

Overview of Model

Objective Function: To maximize the overall net profitability of the system

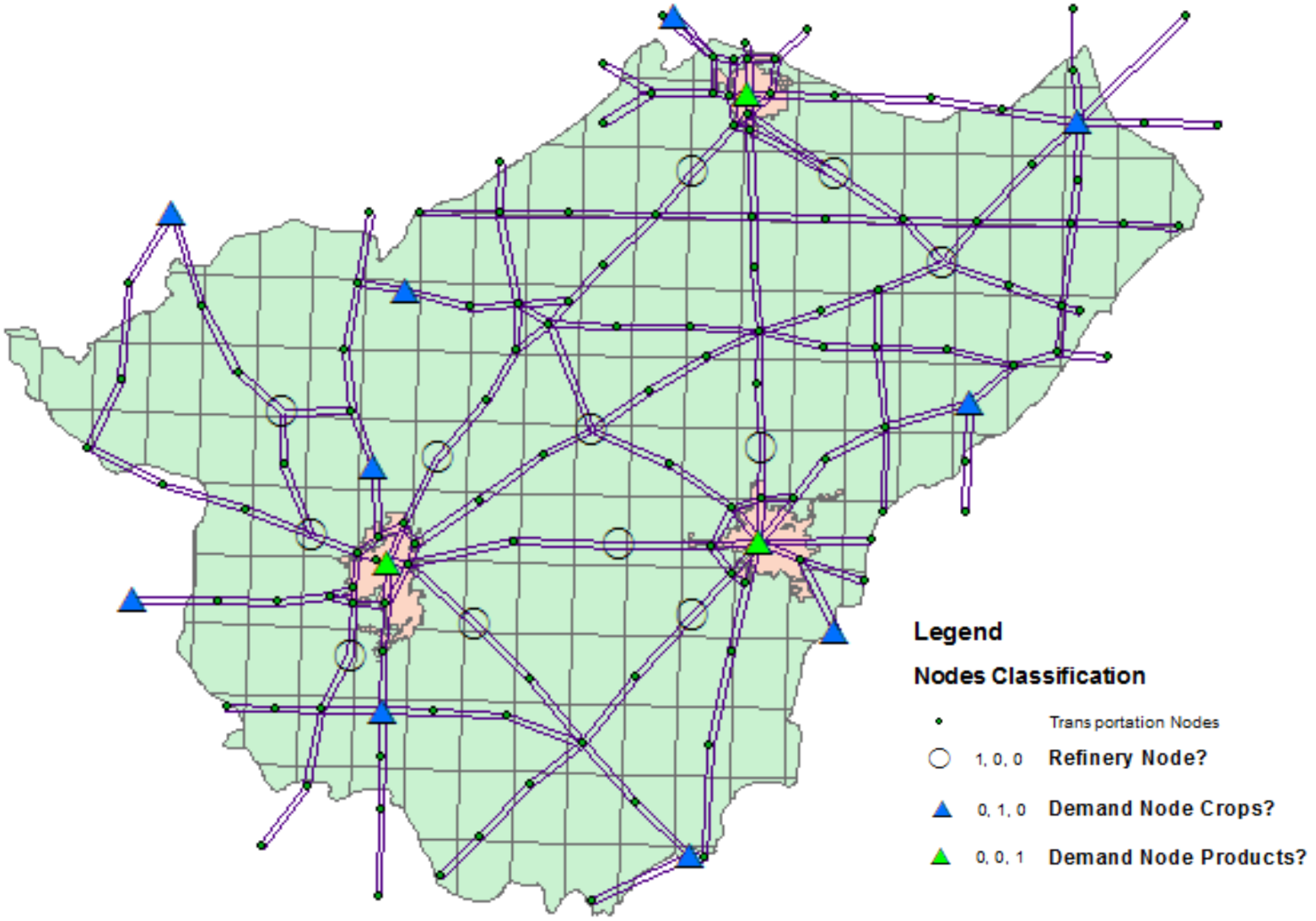
- Profit from selling products
- Capital and operation cost
- Production cost
- Transportation cost

Constraints: Environmental, resources, and infrastructure constraints

Decisions variables

- Allocation of land to crops
- Refinery locations and capacities
- Traffic flow capacities
- Water supply capacities

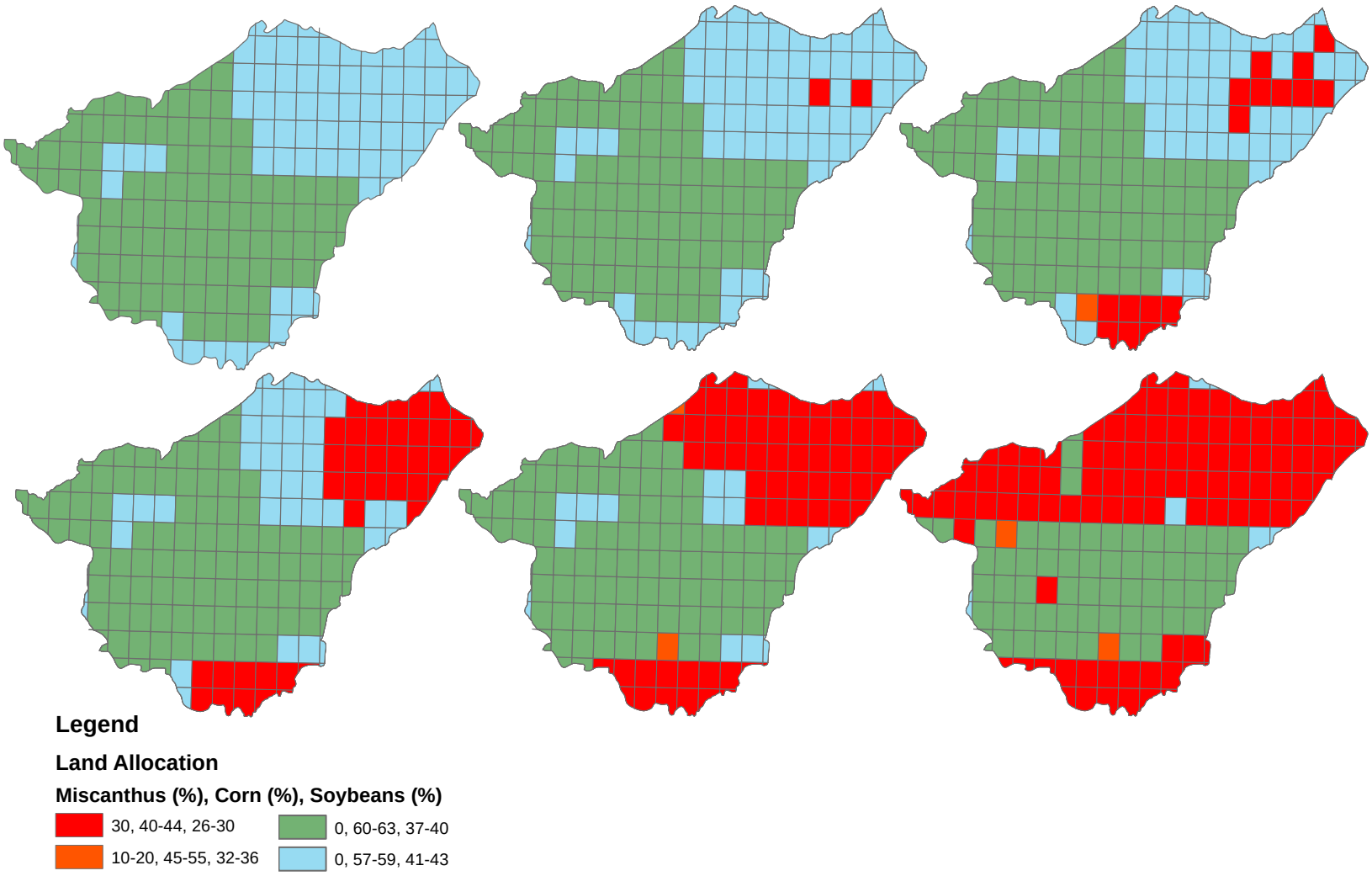
Application to Sangamon Watershed, Illinois



Input Data

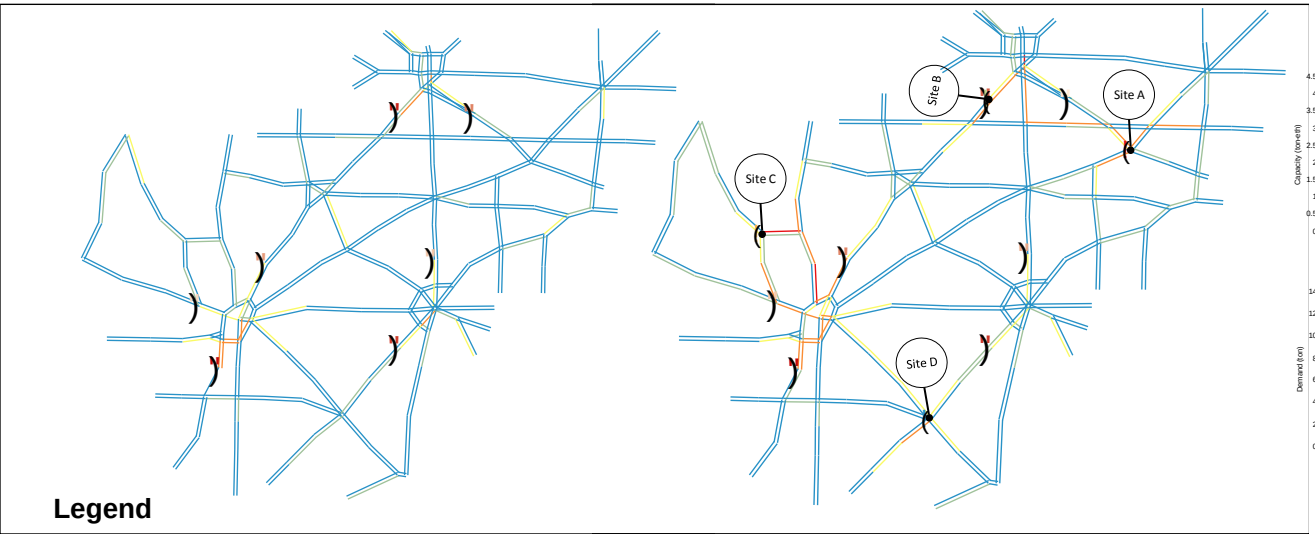
Model Runs

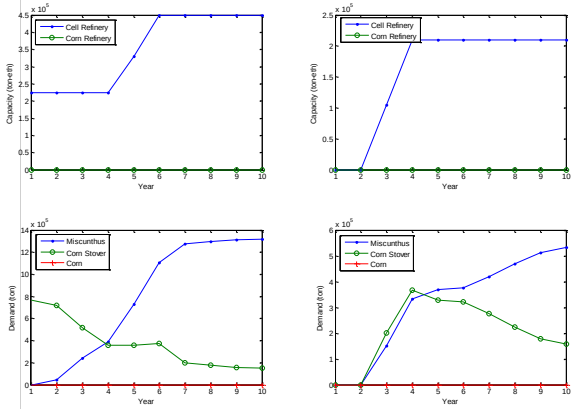
- **Business as usual scenario (BAU)**
- **Impact of Mandate:**
  - RFS mandate (minimum annual production, maximum miscanthus fraction)
- **Transportation infrastructure:**
  - no infrastructure expansion
  - no congestion consideration
- **Environmental constraints:**
  - monthly flow constraint on the watershed outlet
  - monthly flow constraint on the upper Sangamon outlet
  - monthly nitrate constraint on the watershed outlet



Land allocation: BAU Scenario and RFS Scenario in Year 1, Years 2-3, Years 4-5*, years 6-7*, Years 8-10.

* Land allocation in successive years is approximately the same.





Legend

Corn Refinery Capacity (ton)

86926.9032943673	120036.022688597	146619.040626225	187003.22726314
105101.734291998	132769.891661382	164312.275165635	300000
105531.851807649	133016.099091684	169425.103978358	

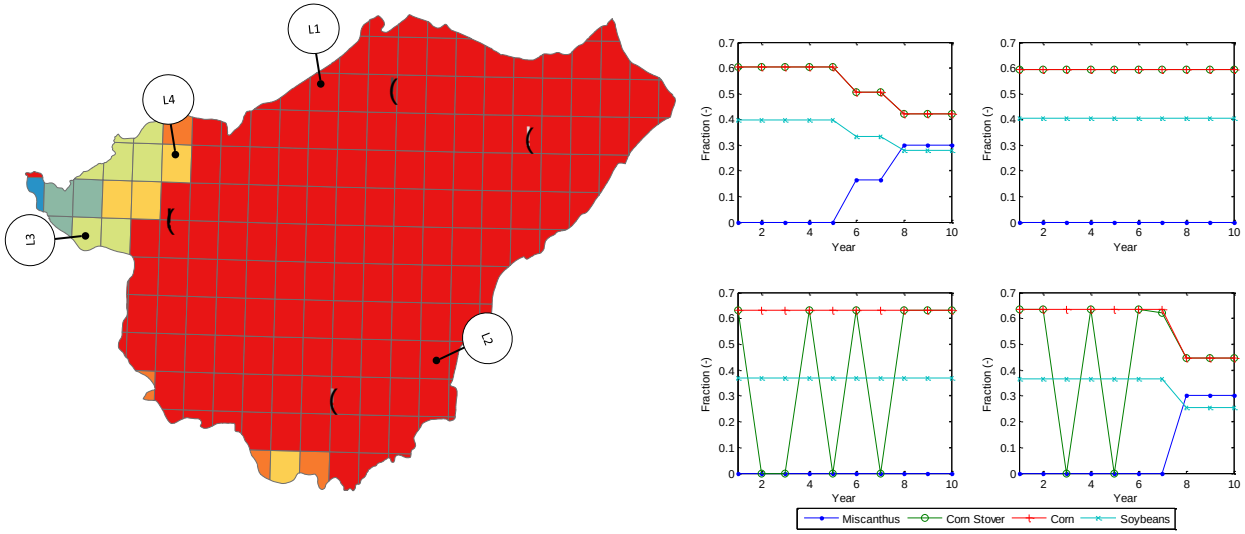
Cell Refinery Capacity (ton)

- 210000
- 240000
- 360000
- 450000

System Traffic (pcphpl)

- .000000 - 2.102002
- 2.102003 - 9.147398
- 9.147399 - 22.438295
- 22.438296 - 43.591052
- 43.591053 - 77.618997

System development at **year 10**: BAU (Left) and RFS (Right). The subfigures show the history of the development for sites A and D (Left to right)



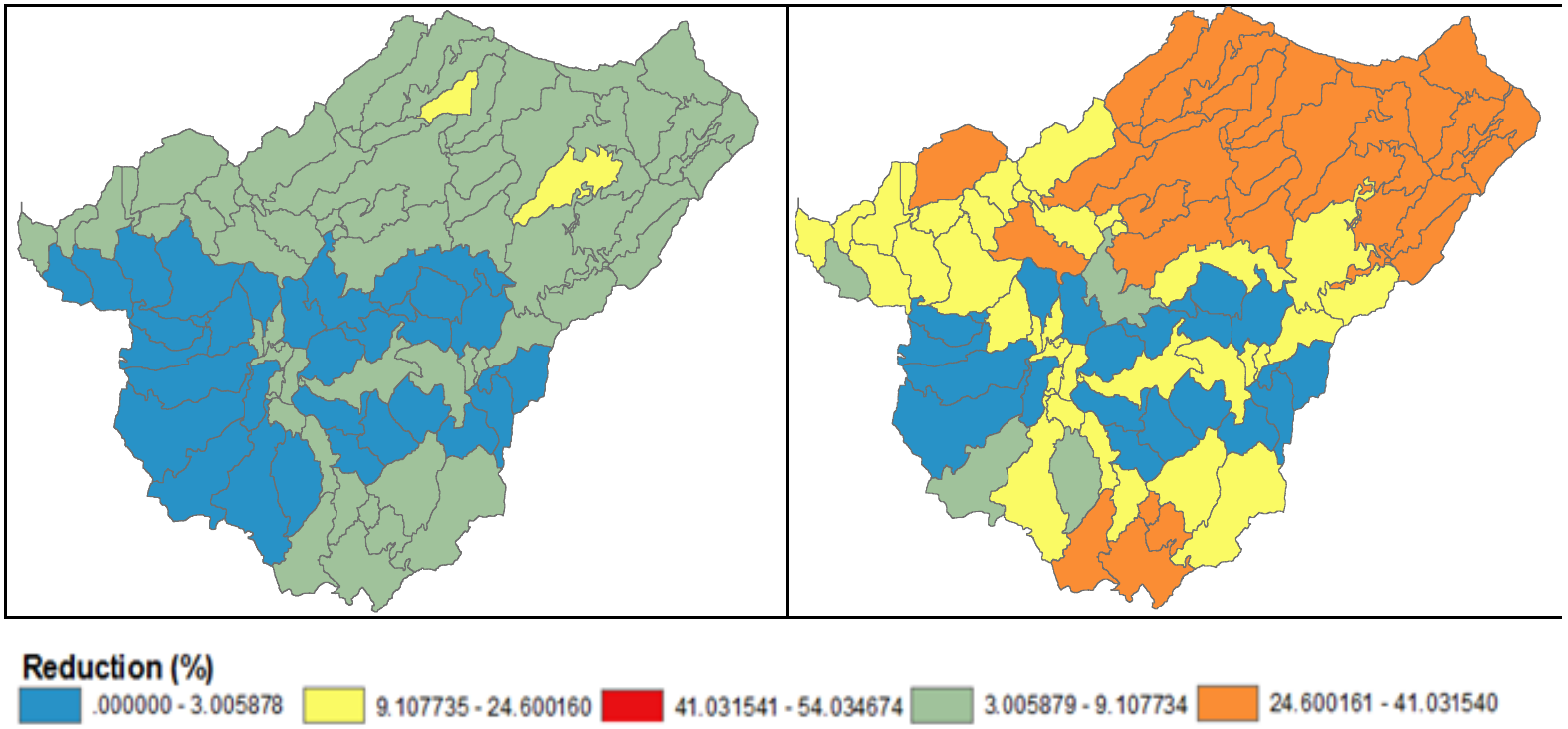
Number of years corn stover is used

- 2.000000
- 2.000001 - 4.000000
- 4.000001 - 6.000000
- 6.000001 - 8.000000
- 8.000001 - 9.990000
- 9.990001 - 10.000000

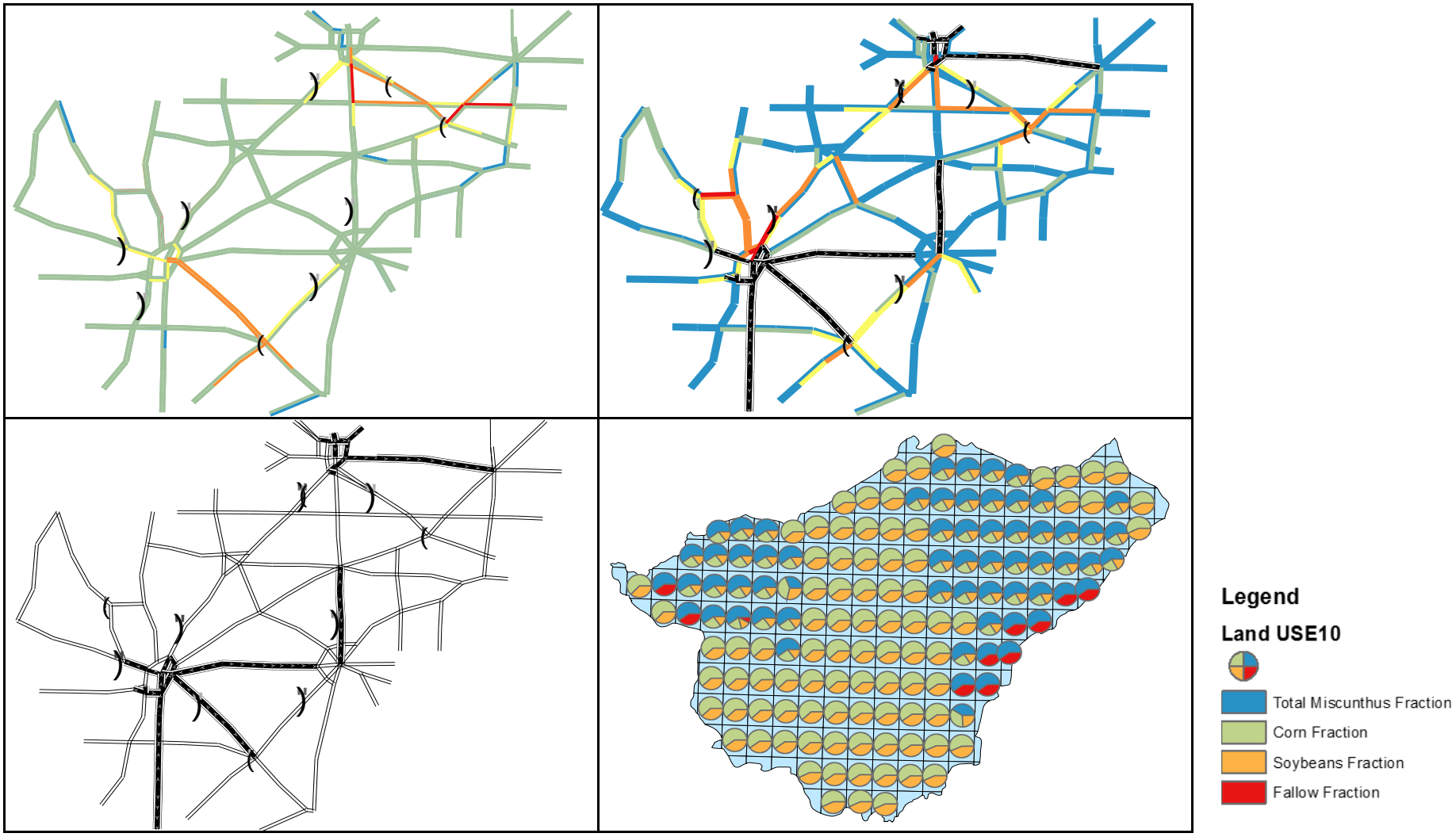
Cellulosic Refinery Built at:

- Year 1
- Year 3
- Year 7
- Year 9

Corn stover utilization in RFS Mandate scenario. The subfigures show the history of the corn stover use in four land parcels L1-L4 (left to right)

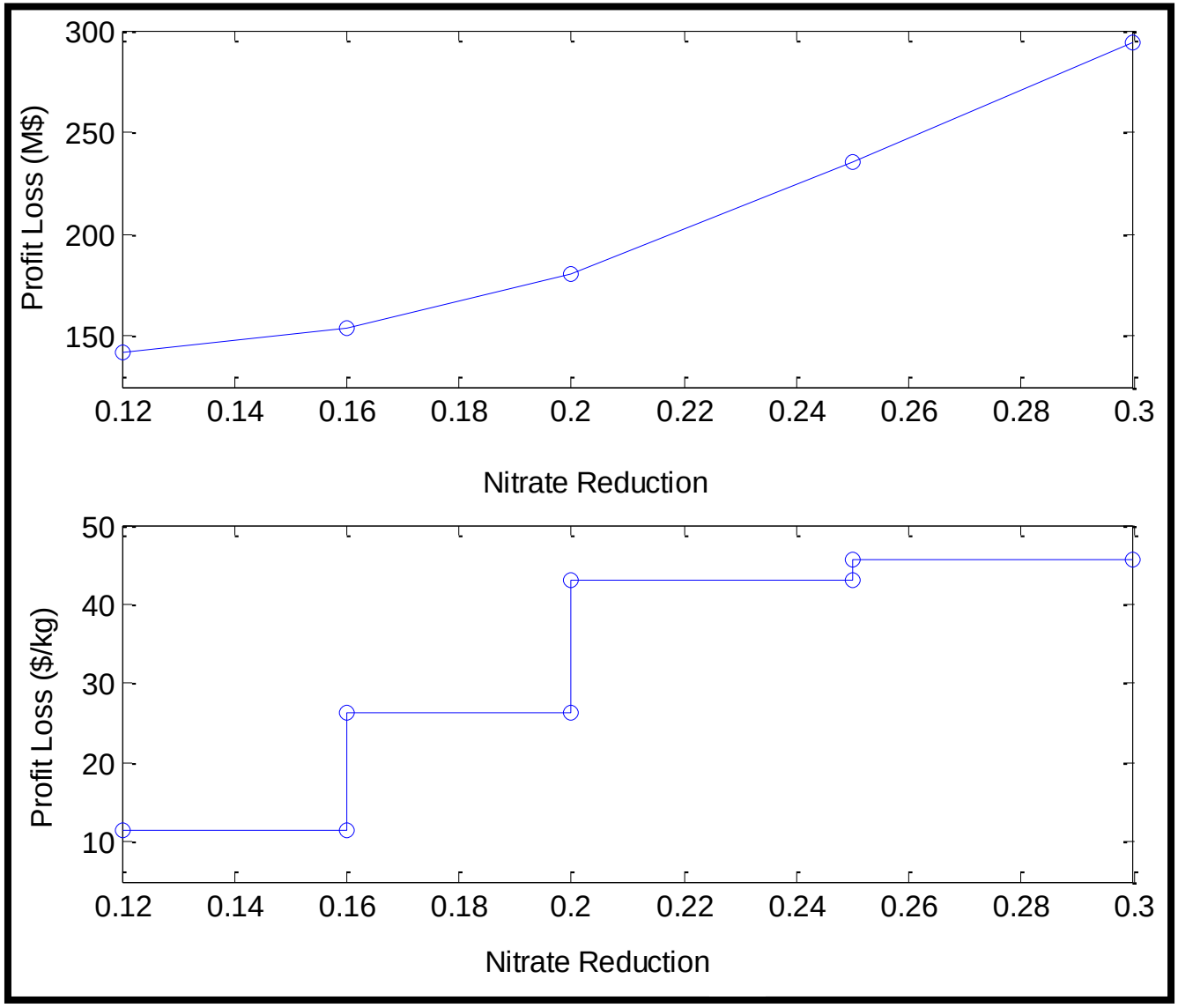


Flow (left) and Nitrate yearly reduction (right) in year 10 compared to BAU



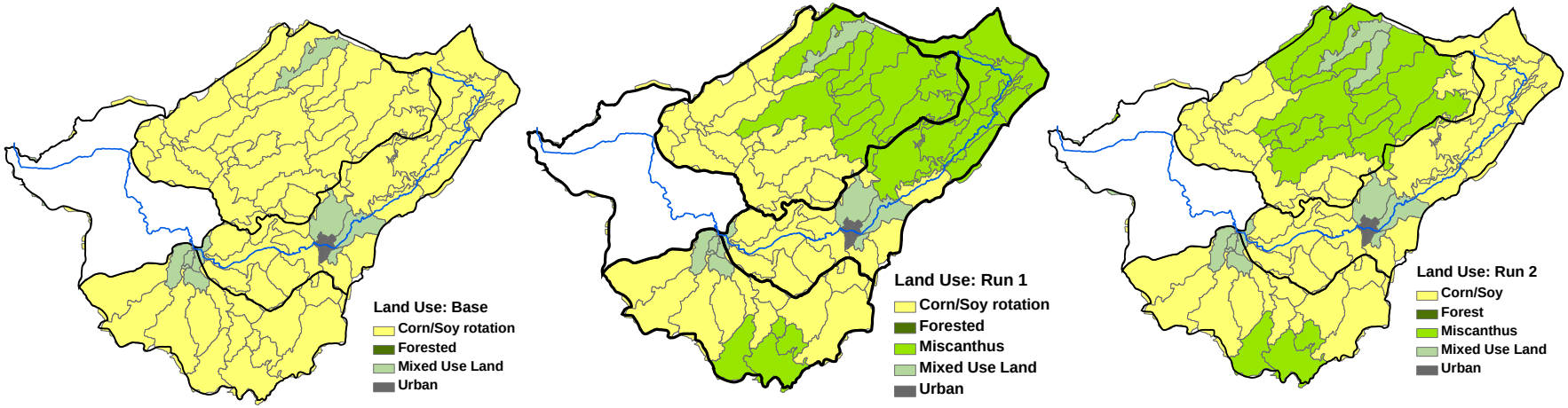
Refineries development at year 10 for RFS 60%, no-expansion, no-congestion (left to right) and the land allocation at year 10 for the environmental scenario

Economical Impacts of Environmental Policies



Imposing different levels of nitrate reduction to examine profit loss

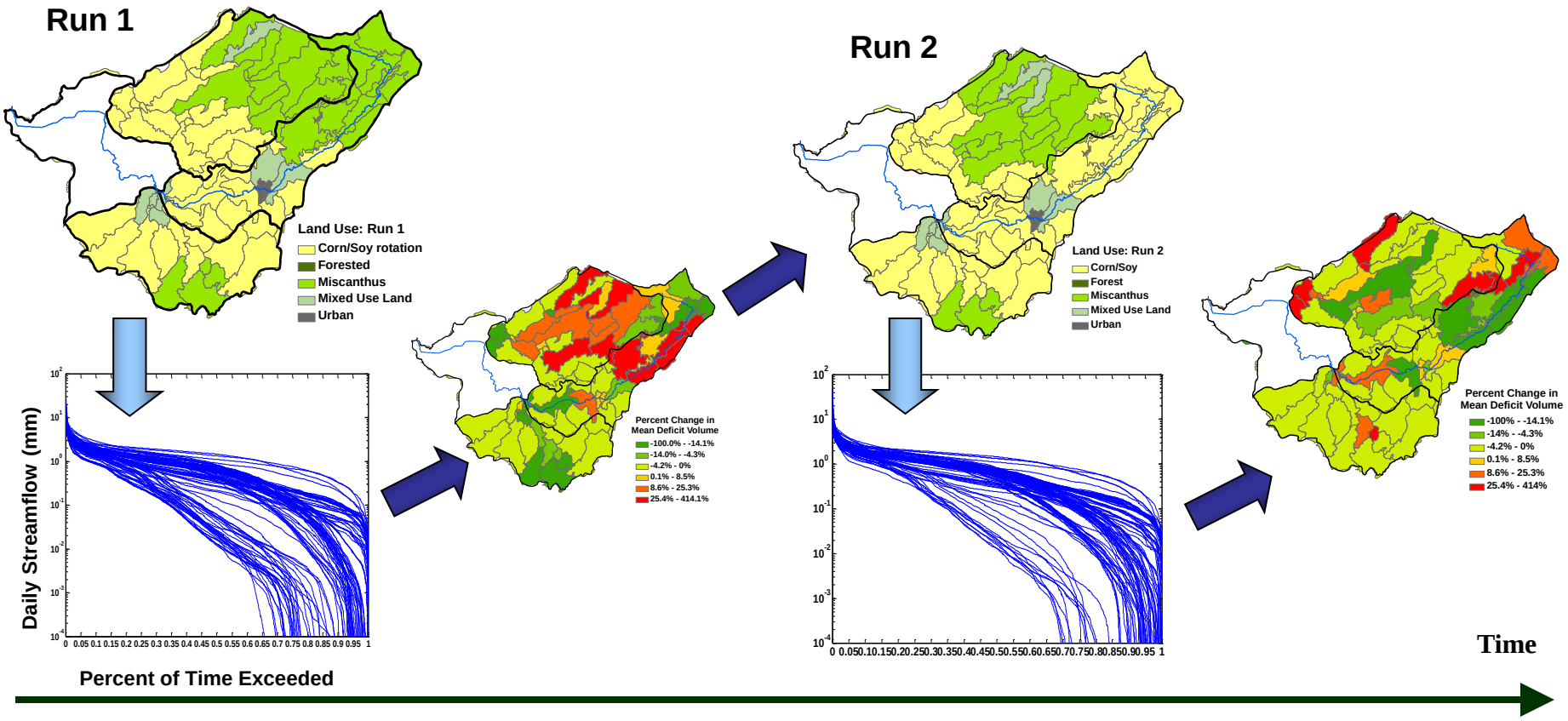
Price, Feedstock Choice and Impact on Flow and Water Quality



- **Base** run is the optimized land use case under current prices and conditions (*left*)
- **Run 1**: an increase of 15% in the price of ethanol (*center*)
  - Economic change that causes *Miscanthus* to become a profitable crop, and thus areas of high *Miscanthus* yield switch to the new crop.
- **Run 2**: a minimum flow requirement ("historical" minimum; here, the Base case) placed at the Monticello gauge (*right*).

(Source: X. Cai group)

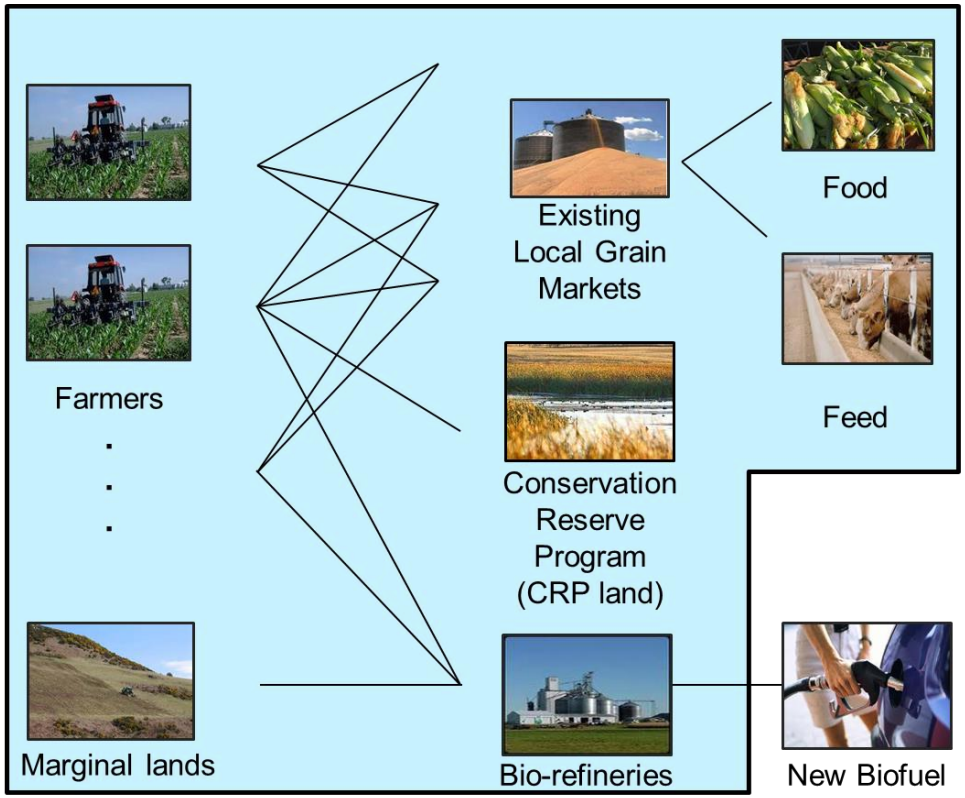
Coupled System Trajectory

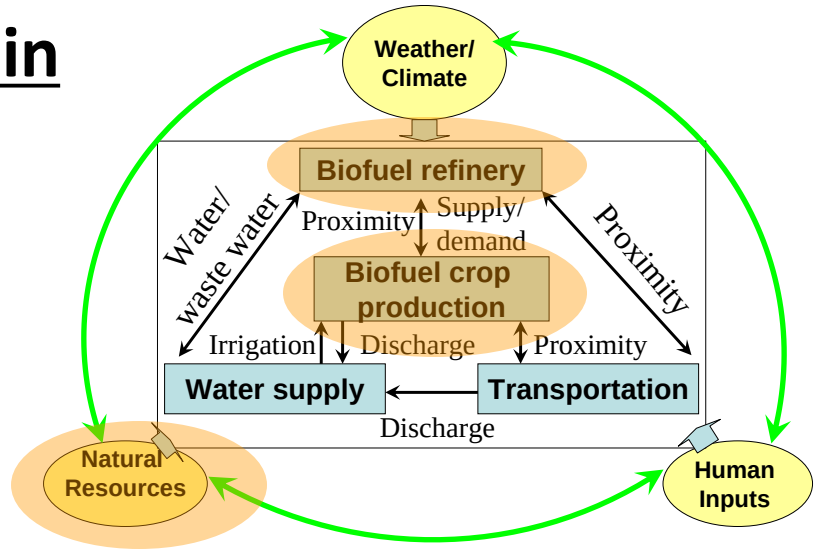


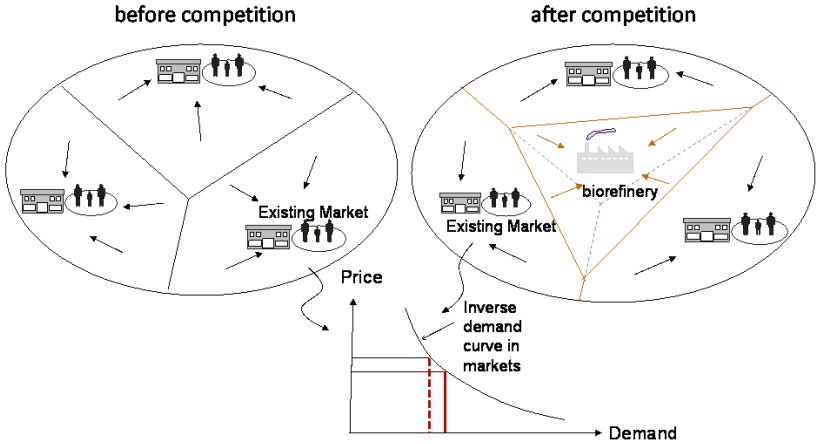
- Shifting the location of Miscanthus within the basin (Run 1 to Run 2) reduced deficit volumes relative to Run 1 (variable response)
  - Effect is shown as percent change in mean deficit volume using Q85 threshold.
- In the south, Miscanthus did not appear to have a large effect on the headwater streams in which it was planted.
  - Effects showed up downstream.

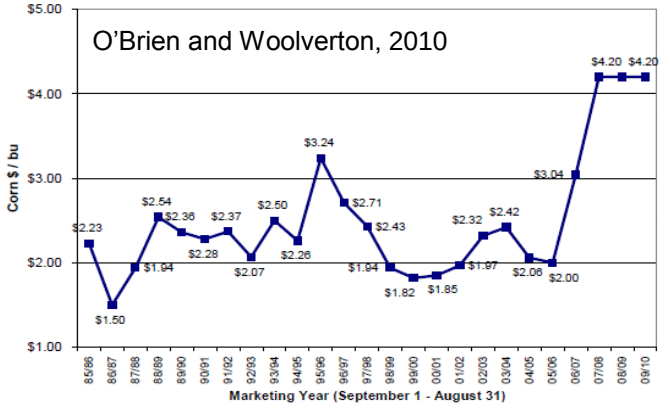
Competitive Biofuel Supply Chain Design under Farmland Use Regulation and Equilibrium

- Interdependencies between biofuel production facility location and (marginal) farm land use under government regulation









Game Theoretic Model Framework

$$\max_{x,\, p_j \geq 0} \quad p_e(\mathbf{f}_J) \sum_{j \in} \qquad - \sum_{j \in J} \left(p_j \sum_{i \in I} f_{ij} \right)$$

$$s.t. \quad \sum_{i \in I}$$

$$x_j \in \{0,1\}, \forall j \in J$$

Biofuel company

$$\sum_{j \in J} \left(f \right.$$

$$\leq \alpha \left[\widehat{r}_i + \sum \; r_{i'} + \sum \left(\widehat{f}_{ik} + \sum_{i' \in I \setminus \{i\}} f_{i'k} \right) \right]$$

Government regulation

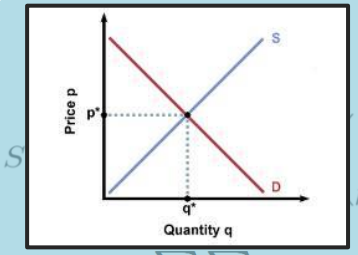
$$\text{maximize} \quad \sum_{m \in M} \widehat{f}_{im} \left[\psi_m \left(\right. \right. \qquad (p_j - d_{ij}) \, \widehat{f}_{ij} + \widehat{r}_i \, p_r \left(\widehat{r}_i + \sum_{i' \in I \setminus \{i\}} r_i \right)$$

$$+ \left(g_i - \widehat{r}_i - \right. \qquad \left. \left. \widehat{f}_{ik} \right] - \sum_{j \in J} \widehat{f}_{ij} \right\} p'_a$$

$$\text{subject to} \quad \widehat{f}_{ij} + \sum_{i' \neq i} f_{i'j} \leq c_j \, x_j, \forall \, j \in J.$$

Farmers

$$0 \leq p_\ell \perp S \qquad \sum_{k \in M \cup J} f_{ik} + r_i \Big) \geq 0,$$



$$0 \leq p'_a \perp E - \sum_{i \in I} \sum_{j \in J} f_{ij} \geq 0$$

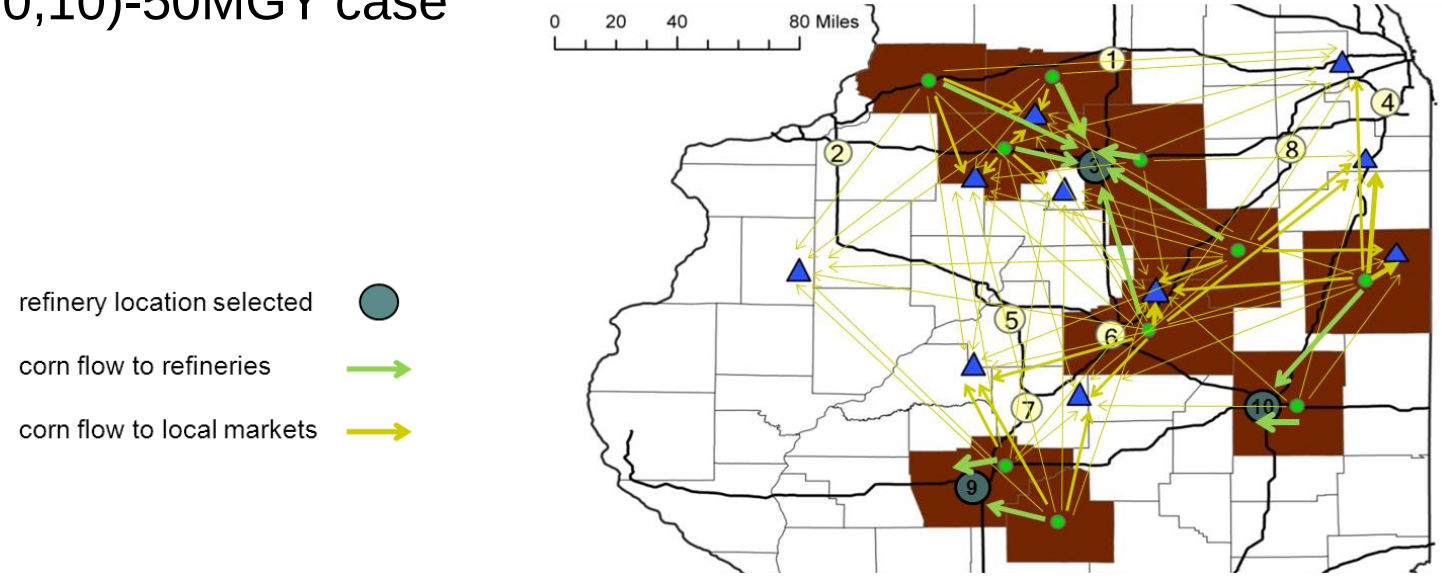
Market equilibrium

Numerical Results

- Comparison with and without land use regulation

(|I|, |J|, |M|)	refinery capacity	scenario	refinery number	farmland use (%)				cost (million $)				revenue (million $)			biofuel industry profit (million $)	social welfare (million $)	pl ($/unit land)	pa ($/unit land)	total permit trading (unit land)
				food crop	energy crop	reseravation	marginal land	total marginal land cost	total transportation cost	total fixed cost	total ethanol production cost	corn sales in food market	ethanol sales in energy market	CRP land revenue					
(10, 10, 10)	25 MGY	P1 (w.o. land use cap)	4	61.0%	32.5%	6.5%	35.9%	238	261	18	847	1174	1988	99	367	2546	1.54	-	-
		P2 (w. land use cap)	4	63.3%	30.0%	6.7%	38.5%	299	208	18	815	1172	1927	96	367	2588	1.73	1.27	219080
	50 MGY	P1 (w.o. land use cap)	2	61.0%	32.5%	6.5%	35.9%	238	218	18	847	1174	1988	99	367	2589	1.54	-	-
		P2 (w. land use cap)	2	63.3%	30.0%	6.7%	38.6%	302	205	18	816	1172	1930	96	367	2592	1.74	1.32	322260
	100 MGY	P1 (w.o. land use cap)	1	61.0%	32.5%	6.5%	35.9%	238	187	18	847	1174	1988	99	367	2620	1.54	-	-
		P2 (w. land use cap)	1	63.3%	30.0%	6.7%	38.6%	302	205	18	816	1172	1930	96	367	2592	1.74	1.32	348663
(30, 30, 30)	25 MGY	P1 (w.o. land use cap)	8	58.8%	36.8%	4.4%	21.1%	348	236	36	1681	2804	4108	177	886	5447	2.64	-	-
		P2 (w. land use cap)	7	65.2%	30.0%	4.8%	20.3%	321	255	32	1362	2968	3422	185	813	5262	2.54	0.13	478835
	50 MGY	P1 (w.o. land use cap)	4	58.6%	37.0%	4.3%	21.2%	349	229	36	1693	2797	4133	177	890	5460	2.64	-	-
		P2 (w. land use cap)	4	65.2%	30.0%	4.8%	20.4%	322	251	36	1362	2968	3423	185	809	5261	2.54	0.14	544973
	100 MGY	P1 (w.o. land use cap)	2	58.6%	37.0%	4.3%	21.2%	349	225	36	1693	2797	4133	177	891	5464	2.64	-	-
		P2 (w. land use cap)	2	65.2%	30.0%	4.8%	20.4%	323	249	36	1362	2969	3424	185	809	5264	2.54	0.15	589969

- Corn supply/demand pattern to elevators and refineries for the (10,10,10)-50MGY case



Applications of the Integrated Model

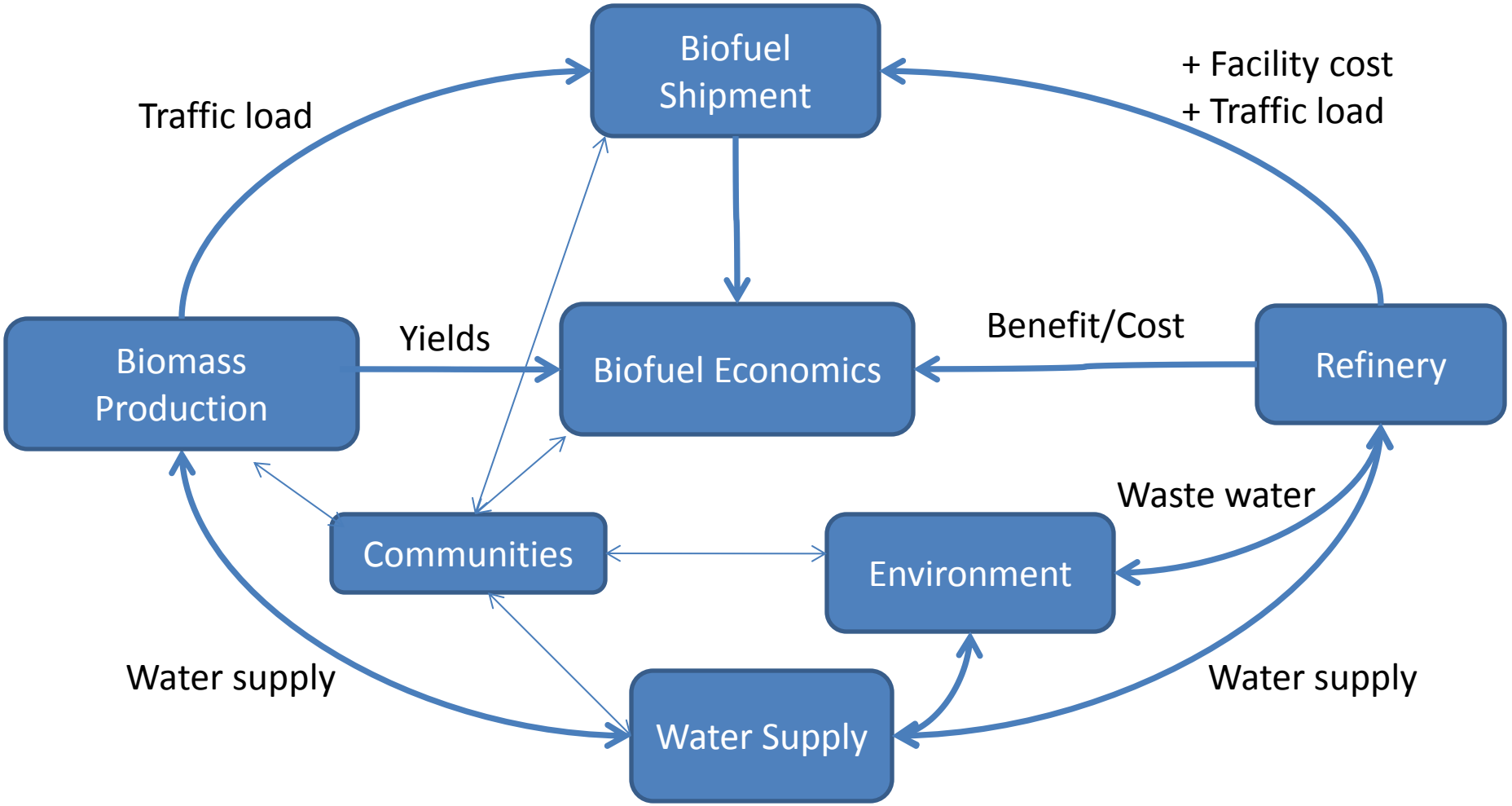
- Sensitivity analysis to model parameters and assumptions
- Scenario analysis
  - Analysis of various scenarios of water availability, possible locations of refineries, climate, etc.
  - In particular, scenarios on system failures for the Insights into how the failure of one sub-system (or a part of it) might affect other sub-systems
- Policy analysis
  - Strategic changes in water supply, transportation system and feedstock production
  - Impact of environmental regulations, climate control policies and technology advances
  - The need of the mix of knowledge, resources and social networks to enable social resiliency
  - Bottlenecks and areas of possible investment/ expansion

Modeling Community Resilience for Biofuel Development

Stephen Gasteyer
Department of Sociology
Michigan State University
509 East Circle Dr, Berkey Hall #316
East Lansing, MI 48824
517-355-3505; gasteyer@msu.edu

Ames, IA July 17-19, 2013

System of Systems



- **Bottleneck infrastructure**
- **Perturbation propagation**
- **Social resilience**

Key Community Aspects

- Socio-economic metrics:
  - Biomass and biofuel productivity
  - Income and social welfares
  - Community development
  - Policy incentives and market development

Risk and Communities in Ethanol Development

- Renewable Energy Technologies involves a calculation of risk by actors in the process:
  - investors
  - developers
  - community residents and leaders
- Risk assessment changes over time based on:
  - internal and external events (including policy changes and market fluctuations)
  - information flows

4 Factors in perceived community risk

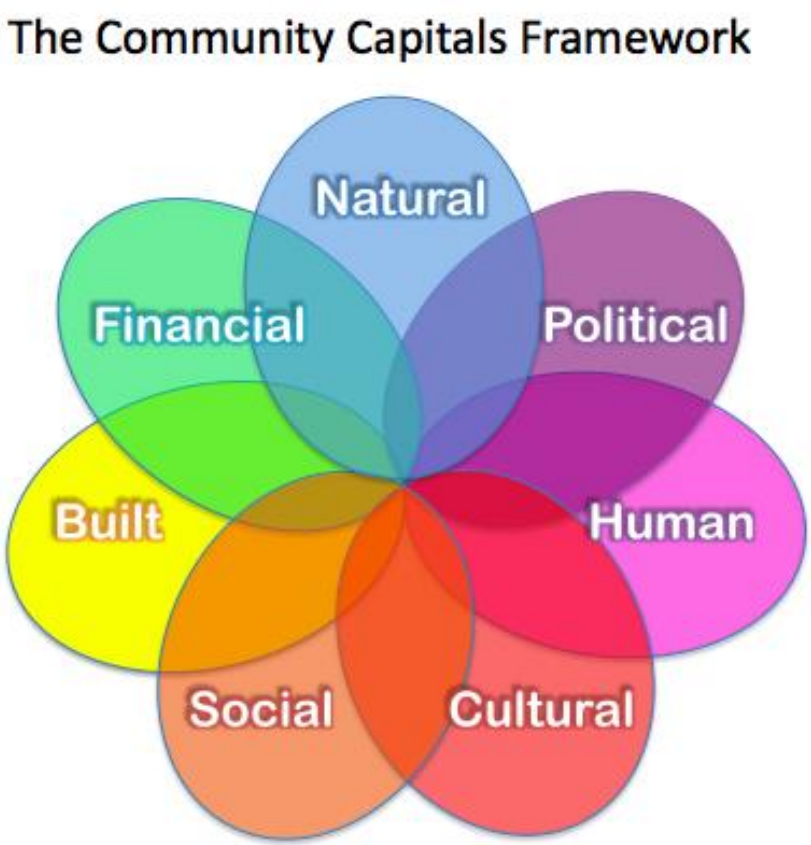
1. Support for ethanol in general (political acceptability of ethanol)
2. Support for the community specific process of siting the facility
3. Readiness of the community to recognize and mitigate risks from siting
4. Impacts of ethanol on community over time

Defining Community Level Outcomes

Natural
Land Use Changes
Scenic Areas
Natural Resources
Agriculture

Built
Vacant Housing
Infrastructure
Water Systems
Road Systems

Financial
Income
Loan Availability
Wealth/Savings



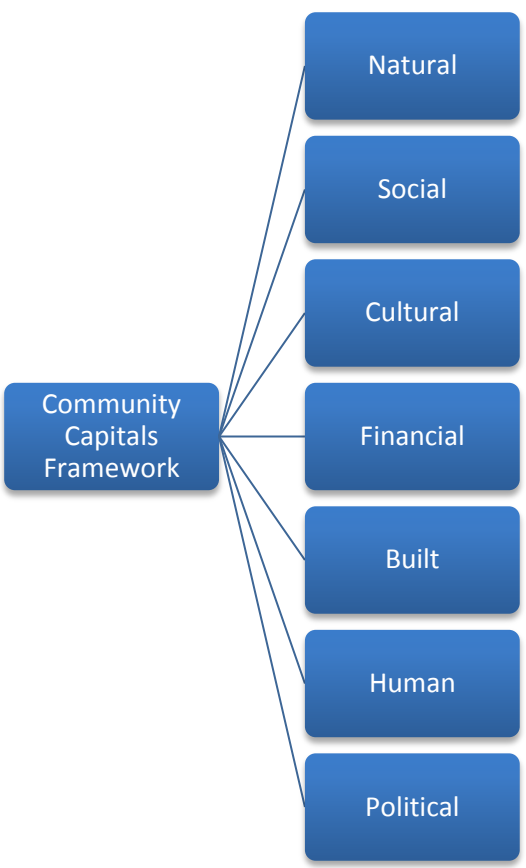
Cultural
Festivals
Celebrations
Arts
Theater

Social
Trust
Reciprocity

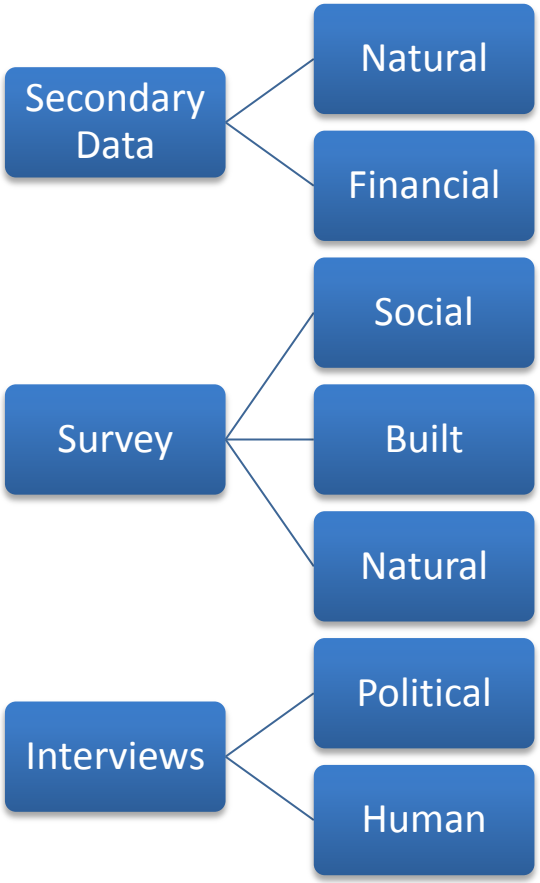
Political
Representation

Human
Education
Knowledge
Skills

Methodology



		Secondary Data Sources
Natural Capital	Perceptions of "natural beauty" and "landscape"	
	Availability of outdoor recreation	
	Toxic Release Inventory (TRI)	X
	Soil Quality	X
	Air Quality	X
	Land Use	X
Cultural Capital	Do community people believe in ability to shape their future?	
	Does your community currently have any Community Festivals?	
	Is there a sense of the community being pro-youth?	
Social Capital	Linkages with other communities	
	Linkages with State or National organizations.	
	Portion of Friends living locally	
	% who were more involved with local than extra-local organizations	
	% who attend church locally	
	% who work locally	
	How far people travel to get to work (stay in community or leave?)	X
	% who stay in home community for recreation and entertainment	
	Are community members Accepting of Change?	
	Number of people volunteering	
	Number of people giving to charities	
	Money donated to charities	
	How long have you lived in this community?	
	When you go to the grocery store, how many people do you usually know by name?	
	How often do you rely on your neighbors or family and how often do they rely on you?	
	Involvement and connectedness to the community. Includes (1) Does family live nearby? (2) Do you visit others homes and do other visit your home?	
Human Capital	Personal Innovation, Responsibility or Initiative? (?)	
	Graduation Rates from elementary school, middle school and high school	X
	Out-migration /re-migration of educated population?	X
	Education levels of community members	X
	Change in % of people of working age (18 to 64)	X
	Change in % of Employed or Unemployed people	X
	Population Change	X
	Quality of health care	
	Quality of childcare	
	Adult education available?	
Political Capital	Community and government connections at various levels?	
	Leadership connections	
	Diversity of leadership	
Financial Capital	Outside funding?	
	Number of Scholarships awarded to high school seniors?	
	Funding from state agencies?	
	Local business links to global markets?	
	Investments in local business development	
	Poverty reduction	X
	Businesses grow, change hands, open or close?	
	Change in number of small businesses	X
	Income	X
	# of entrepreneurs	
Built Capital	Local businesses use of technology	
	Transfer of ownership from the older generations to younger generations?	
	Change in Vacant Housing Units	X
	Local industries # increasing/ Decreasing?	X



1. General Support for Ethanol: Cultural Capital

- Strong correlation in USA between geographic and economic connection to commodity agriculture and support for ethanol and biodiesel.
  - Champaign Illinois as example
- Indicator: percent of economy connected to agriculture
  - (0=less than 1% in commodity production; 1=Agriculturally Dependent County)

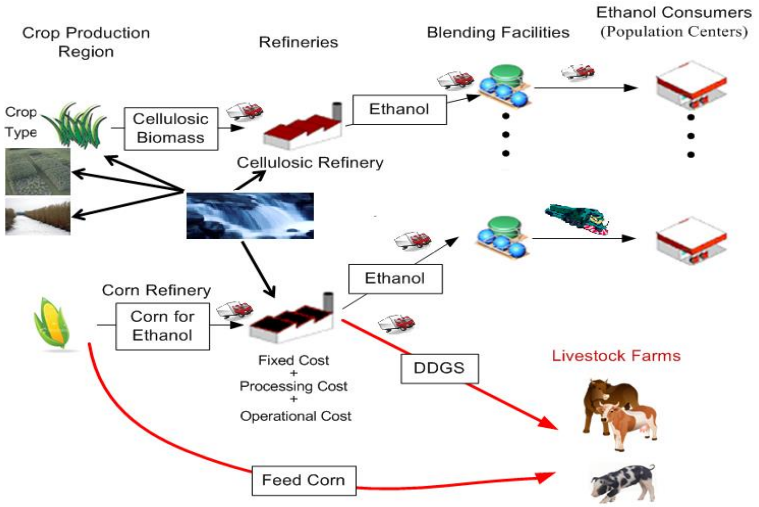
2. Support for local ethanol process

- Extent to which community has experienced failed ethanol siting.
- 2008-2009 led to closure of many facilities
- People in those communities and neighboring communities view risks as greater.
- Indicator – proximity to a community where plant has closed in last decade.
  - 0=plant closed locals lost money; .25=plant closed; .5 neighboring community plant closed; .75=plant closed in neighboring county; 1=no plant closures in area

3. Community Readiness

- Capacity to recognize and mitigate risks
  - Proximity to feedstocks and markets
    - Feedstocks: 0-1 based on distance that feedstock shipped
    - Markets: 0-1 based on distance that produced fuel shipped to blending facility

		Urban or Rural		
		Rural	Urban	Total
Is there a biofuel facility in the county?	Existing Biofuel Facility	3 25.0%	9 75.0%	12 100.0%
	Proposed Biofuel Facility	19 59.4%	13 40.6%	32 100.0%
	No Biofuel Facility	37 63.8%	21 36.2%	58 100.0%
	Total	59 57.8%	43 42.2%	102 100.0%



3: Community Readiness

- Human capital: Skill set to mitigate risks to social services and to fill positions –
  - Indicators:
    - operator CWS rankings (Survey);
    - % pop with technical degrees (Census)
- Social capacity: Institutional mechanisms to mitigate affordability and complaints
  - Indicator:
    - zoning regulations in place (Interview);
    - social services staff per capita (Interview);
    - social services NGOs per capita (IRS)

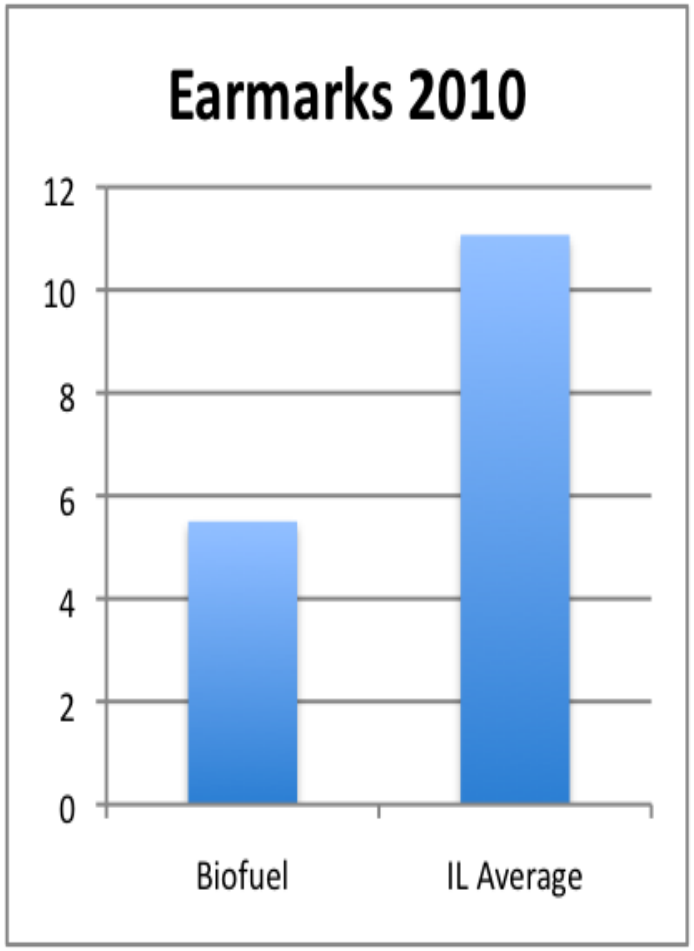
Table 1. Comparing Capacity of Water Systems with Existing or Proposed Facilities

	Existing Facility	Proposed Facility	None
Financial Capacity	10.3	10.9	11.7
Management Capacity	7.8*	9.2*	10.2*
Technical Capacity	10.3	10.6*	9.6*
Operator Capacity	9.6	9.4	8.9

*p-value < 0.05

3: Community Readiness

- Political capital: connections to government to bring resources to mitigate risks
  - Indicators
  - earmarks (OMB);
  - government grants (OMB)
- Social Capital – Trust
  - Whether people felt involved in the process –
  - Indicator (interview): Changes in design due to concerns



3. Readiness – Resilience and Robustness

- Built capital: Flexibility in plant design
  - Can the plant produce other products when ethanol market dries up?
    - Where are the markets for those products
- Built, Social, Financial Capital
  - Economic diversity: diversity of non-farm economic activity
- Social-Financial: Ownership model – who invested – who puts up capital; how are returns divided?
  - Coop, Local LLC, outside investor
  - Community investment

4. Community impacts

- Jobs created; businesses created
  - Extent to which local residents benefit (change in unemployment)
- Changes in median household income
  - For whom—farmers, community residents;
  - Changes in income disparity
- Changes in investment in local services and infrastructure – upgrades to roads, water, etc.
- Changes in deterioration in local infrastructure
  - Water supply; toxic releases; air quality; energy; road use;

Integrating Community Resilience

- We are now working to integrate this data into our model for ethanol facilities in Illinois.
- The factors modeled will be 1, 2, and 3 with a prediction of impacts over time.
- These factors will be important for both corn ethanol and perennial grass ethanol. There may will be adjustments needed as the latter systems are beginning to be developed using more distributed (and flexible) production models

Summary

- Work at both system level and subsystem level provides guidance to crop choice, price choice, refinery and shipment facility location and size, strategies for infrastructure design and management

- The interaction between environmental, social and engineering systems will lead to radically new technology in biomass production, biofuel refinery and shipment and associated infrastructure expansion

- Understanding of the dynamics of a “system of systems” will lead to paradigm shifts in the expansion of interdependent engineering infrastructures