A Spatially Explicit Watershed Scale Optimization of Cellulosic Biofuels Production

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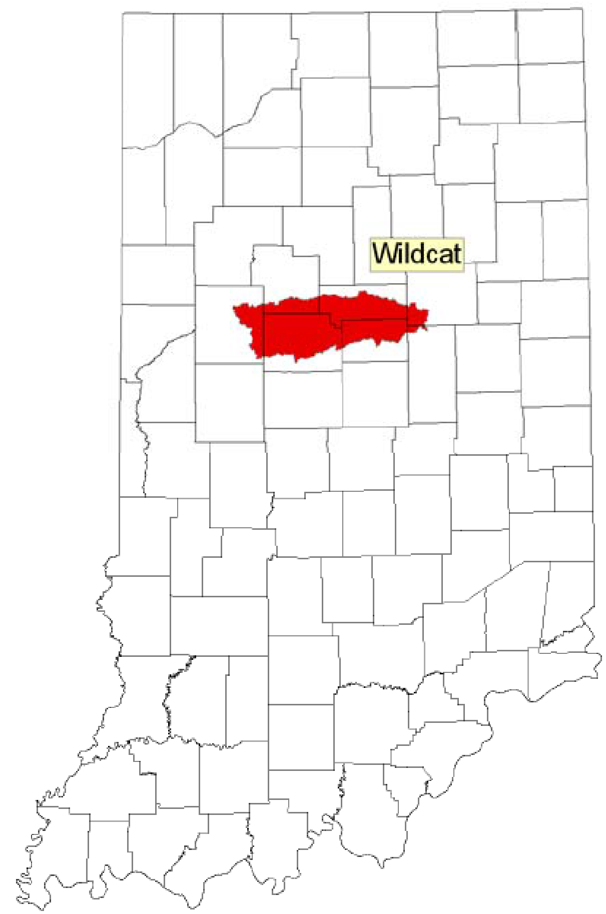
Background

- The United States relies heavily on nonrenewable energy sources
- Energy security and degradation of the environment
- Cleaner and more environmentally friendly energy sources?

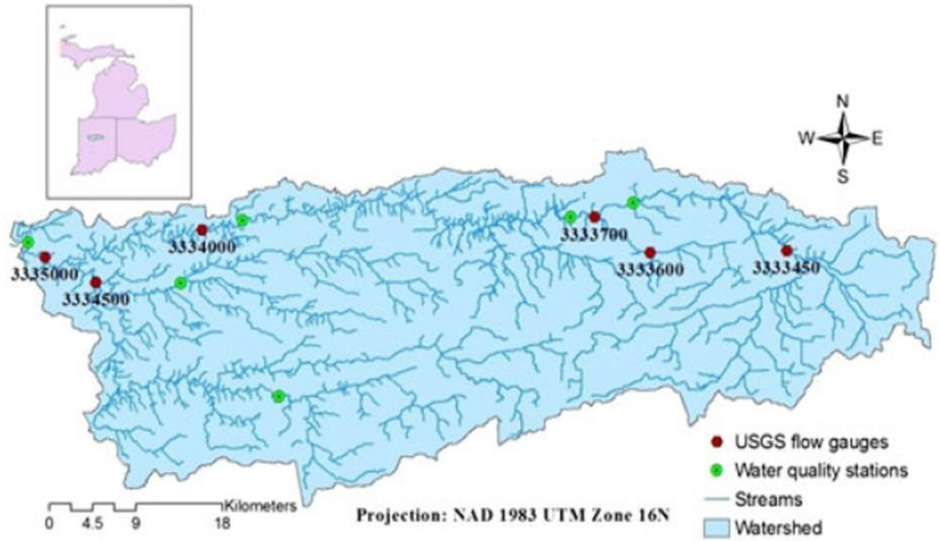
Expected Types of Biomass by Geographic Region in the US. ("Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda", 2006)

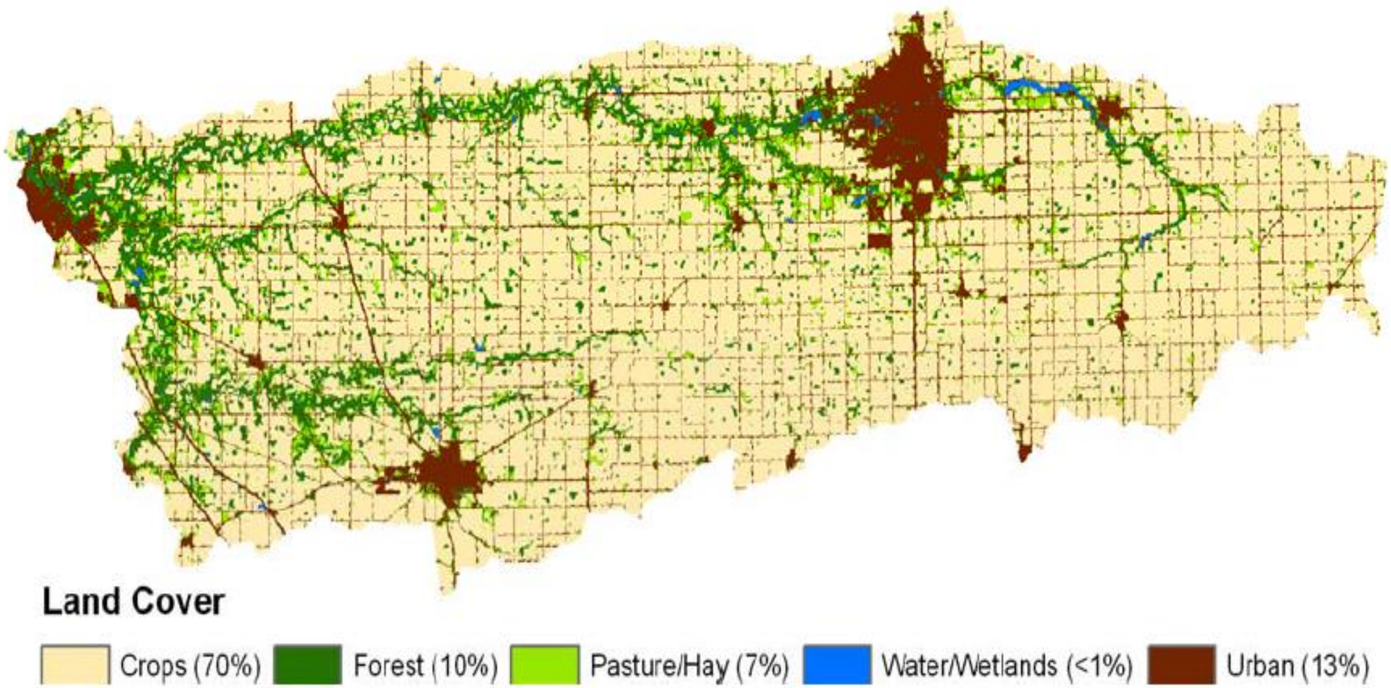
- This research:
  - Combination of Environmental analysis and Economics
  - Spatially explicit sustainability assessment of cellulosic bioenergy crop production
  - A gap in the literature is filled by taking into account both the economic and the environmental sides of biofuel production

- The watershed studied in this project is the Wildcat Creek, which is located in North-Central Indiana

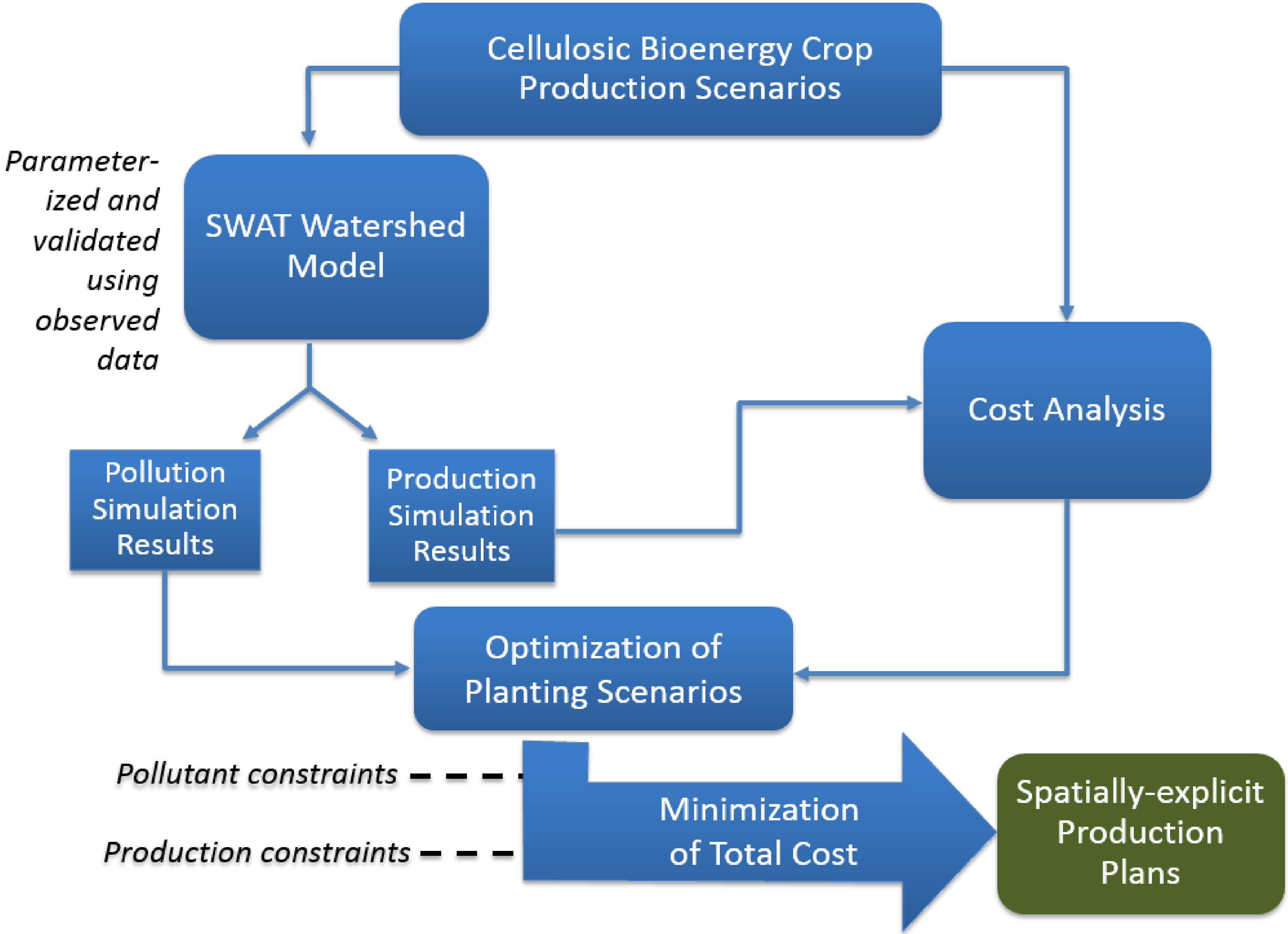


- About the watershed:
  - approximately 150 km long, 2,083 km^2
  - drains to the Wabash River





Structure



Cellulosic Bioenergy Crop Production Scenarios
Parameter-ized and validated using observed data
SWAT Watershed Model
Cost Analysis
Pollution Simulation Results
Production Simulation Results
Optimization of Planting Scenarios
Pollutant constraints
Production constraints
Minimization of Total Cost
Spatially-explicit Production Plans

Cost Minimization Problem

Objective function:

$$TotalCost\ (\$) = \sum_{i=1}^{n=918} ProductionCost_i + LoadingUnloadingCost_i + HaulingCost_i, \forall\ i$$

s.t.

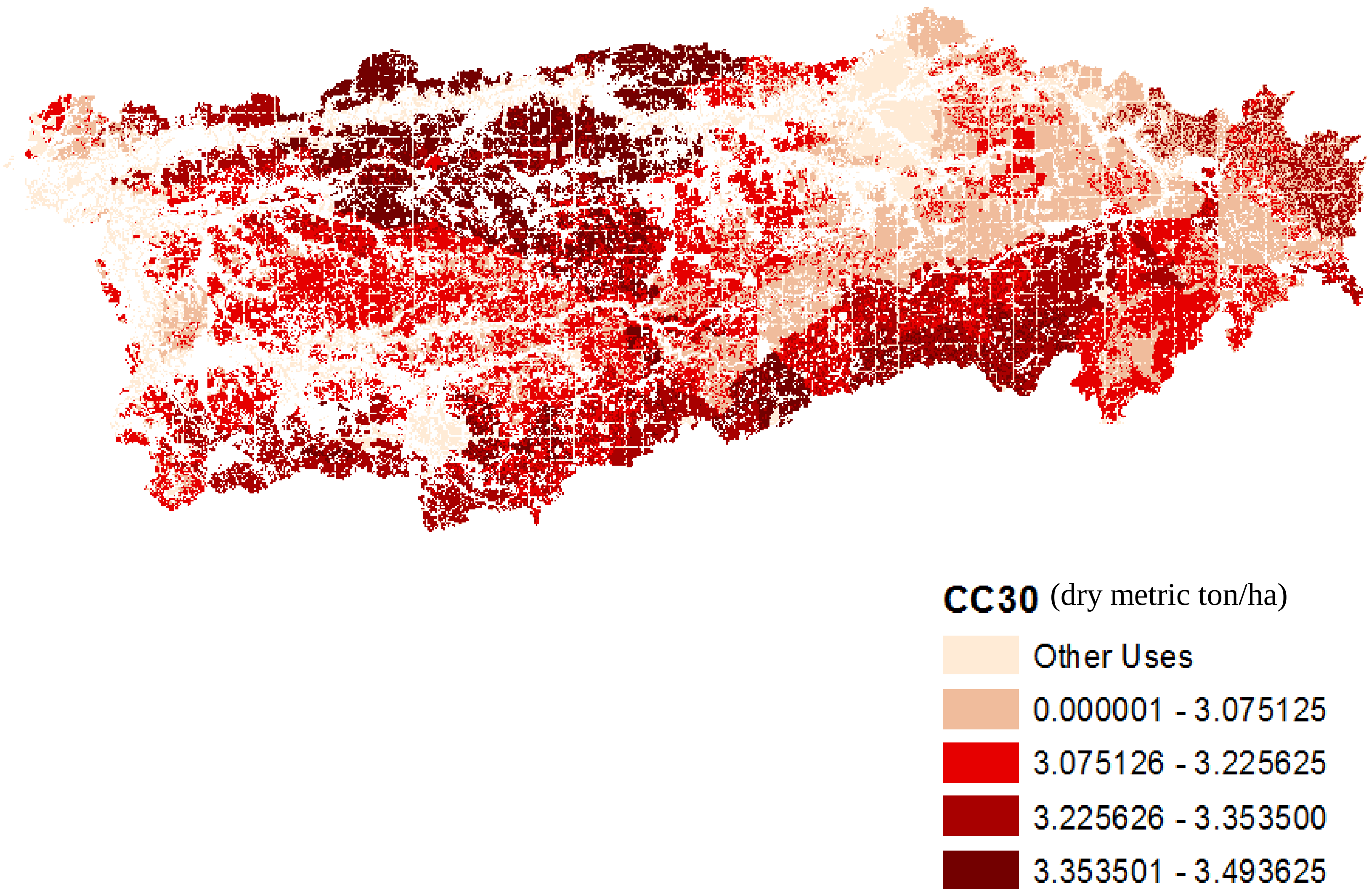
- $Total\ Production\ \geq minimum\ input\ capacity\ (metric\ tons)$
  - Thermochemical: 1,307,065 metric tons
  - Biochemical: 858,480 metric tons
- $TotalSediment(metric\ ton) \leq BaselineTotalSediment(metric\ ton) * ReductionRate$
- $TotalN\ (kg) \leq BaselineTotalN(kg) * ReductionRate$
- $TotalP\ (kg) \leq BaselineTotalP(kg) * ReductionRate$

Cropping Scenarios Examined

Baseline	**Residue Removal**	**Perennials**
Corn-Soybean (CS) rotation, *no residue removal*	Corn-Soybean (CS) rotation, 2 scenarios: 30% residue removal (CS30), CS50	Switchgrass (SG)
	Continuous Corn (CC), 3 scenarios: 20% residue removal (CC20), CC30, CC50	Switchgrass, No-Till planted (SGNoTill)
		Miscanthus (Mxg)

SWAT Results for Biomass Yield

Scenario	Biomass Yield (dry metric tons/ha)	Total Production (metric tons, entire watershed)
Baseline CS	0	0
CC20	2.11	306,475
CS30	3.02	219,048
CS50	5.13	371,502
CC30	3.18	461,092
CC50	5.32	770,681
Switchgrass	10.65	1,543,463
SwitchgrassNoTill	10.65	1,543,226
Miscanthus	20.64	2,991,663


CC30 (dry metric ton/ha)
Other Uses
0.000001 - 3.075125
3.075126 - 3.225625
3.225626 - 3.353500
3.353501 - 3.493625

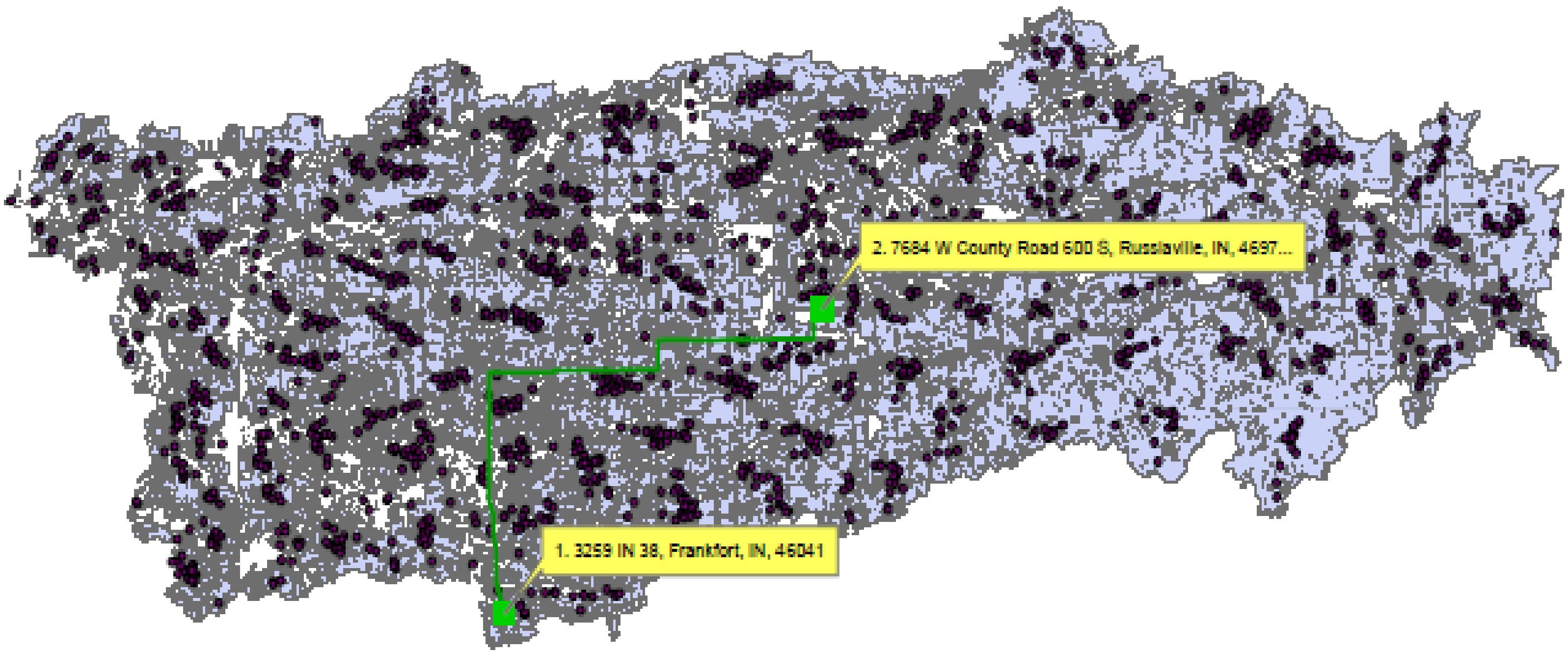
Pollutant Loadings under Each Scenario

Scenario	Sediment (metric ton/ha)	Total Sediment (metric tons)	N (kg/ha)	Total N (kg)	P (kg/ha)	Total P (kg)
Baseline CS	2.76	400,258	36.24	5,252,363	3.87	560,299
CC20	2.09	303,221	60.69	8,795,061	7.13	1,032,836
CS30	2.27	328,430	35.58	5,156,636	6.93	1,004,513
CS50	2.34	338,534	35.53	5,148,937	7.04	1,019,666
CC30	2.11	306,293	59.35	8,601,283	7.18	1,040,536
CC50	2.20	319,269	55.39	8,026,275	7.29	1,056,324
Switchgrass	0.01	1,616	16.22	2,351,037	0.09	12,641
SwitchgrassNoTill	0.01	1,616	16.22	2,350,941	0.10	14,630
Miscanthus	0.01	1,433	10.32	1,494,803	0.06	8,411

Loading and Unloading Cost for Large Round Bales

Activity	Time (hrs)	Unit Cost	Corn	SG & Mxg	Source
Loading ($/bale)			1.15	1.15	Petrolia (2008)
Unloading ($/bale)			1.15	1.15	
Truck Wait ($/bale)	1.329	19.68	0.87	0.87	Thompson & Tyner (2014)
Oversize Permit ($/bale)			0.02	0.02	Author's estimate
Total ($/bale)			3.45	3.45	Converted to 2014 dollars

Routing for Hauling Cost Calculations

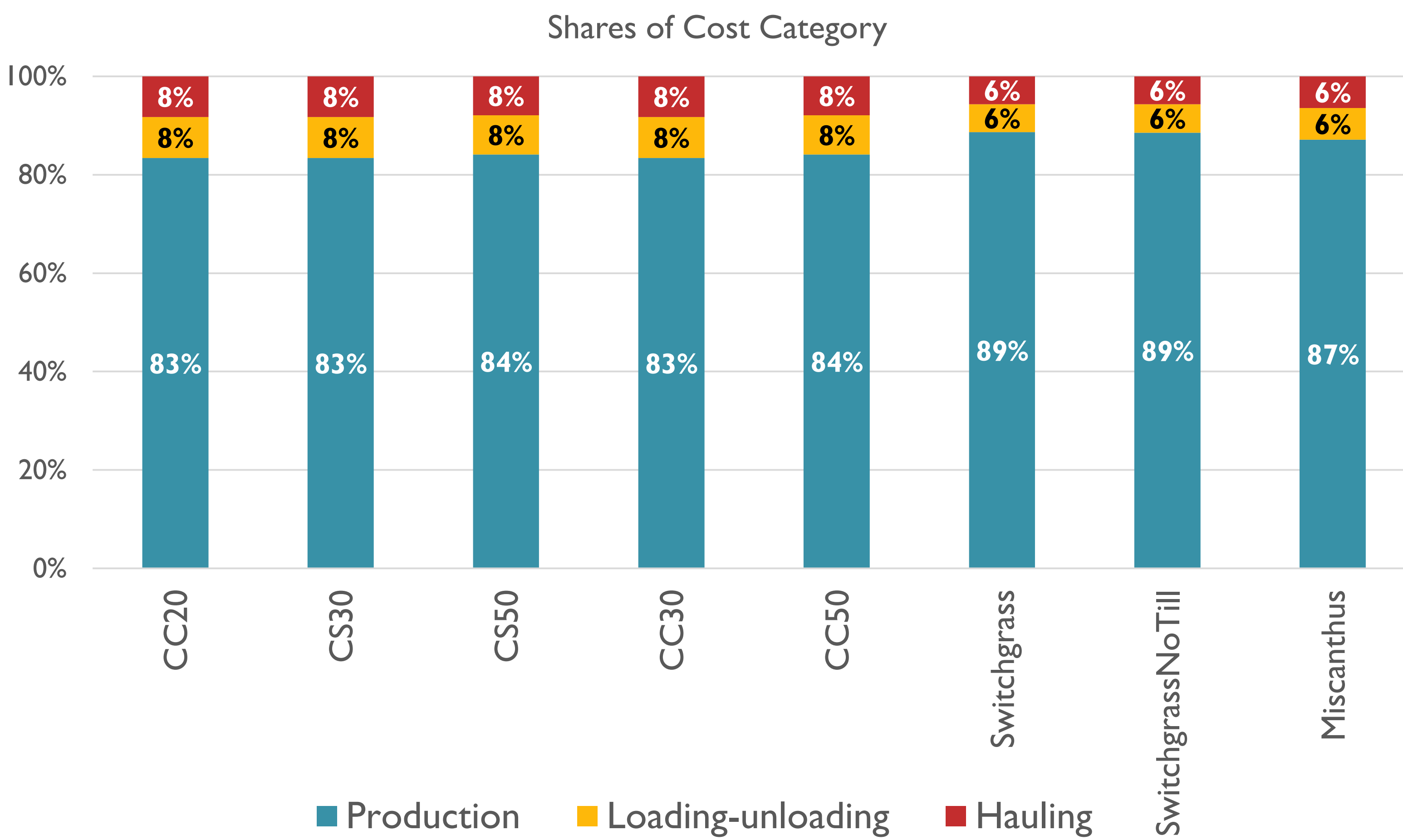


- Captured from ArcGIS "Find Route" result
- Dark spots are centroids for HRUs

Costs for Each Cropping Scenario

Scenario	Unit Production Cost ($/ha)	Production ($)	Loading-unloading ($)	Hauling ($)	Total Cost ($)
Baseline CS	0	0	0	0	0
CC20	126.34	18,308,257	1,830,521	1,813,618	21,952,396
CS30	90.30	13,085,532	1,308,762	1,296,749	15,691,043
CS50	161.30	23,374,077	2,218,639	2,197,708	27,790,423
CC30	190.08	27,544,855	2,753,227	2,727,357	33,025,439
CC50	334.00	48,401,540	4,600,804	4,556,210	57,558,555
Switchgrass	1,253.73	181,681,425	11,699,516	11,585,356	204,966,297
SwitchgrassNoTill	1,245.30	180,460,890	11,697,704	11,583,978	203,742,572
Miscanthus	2,108.50	305,549,860	22,675,397	22,551,770	350,777,026

Cost Shares of Production, Loading-unloading and Hauling



**Percentages may not sum to 100% due to rounding*

How does the model work?

- GA is a direct, parallel, stochastic method for global search and optimization, which imitates the evolution of the living beings, described by Charles Darwin (Popov, 2005).

- Three processes
  - Selection. As all the individuals enter the selection process, the rule, survival of the fittest, will select the best individuals to survive and transfer their genes to the next generation.
  - Crossover. The genes of the parents are used to form entirely new combinations.
  - Mutation. The last procedure, introduces random change to the values that result from the previous two processes.

- Multi-Level Spatial Optimization (MLSOPT*):
  - Split the optimization problem into more reasonably-sized sub-watershed
  - Optimization for each sub-watershed
  - Merge all samples to form a new sample population for the watershed
  - Optimization at watershed scale

* Raj and Chaubey (2015), *Environmental Modelling & Software, vol. 66, 1-11*

Optimization Results (production constraint)

Thermochemical biorefinery

- Total cost: $124,754,326
- Total biomass production: 1,307,066 metric tons per year
- CC50 (73%), Mxg (25%), baseline (2%)

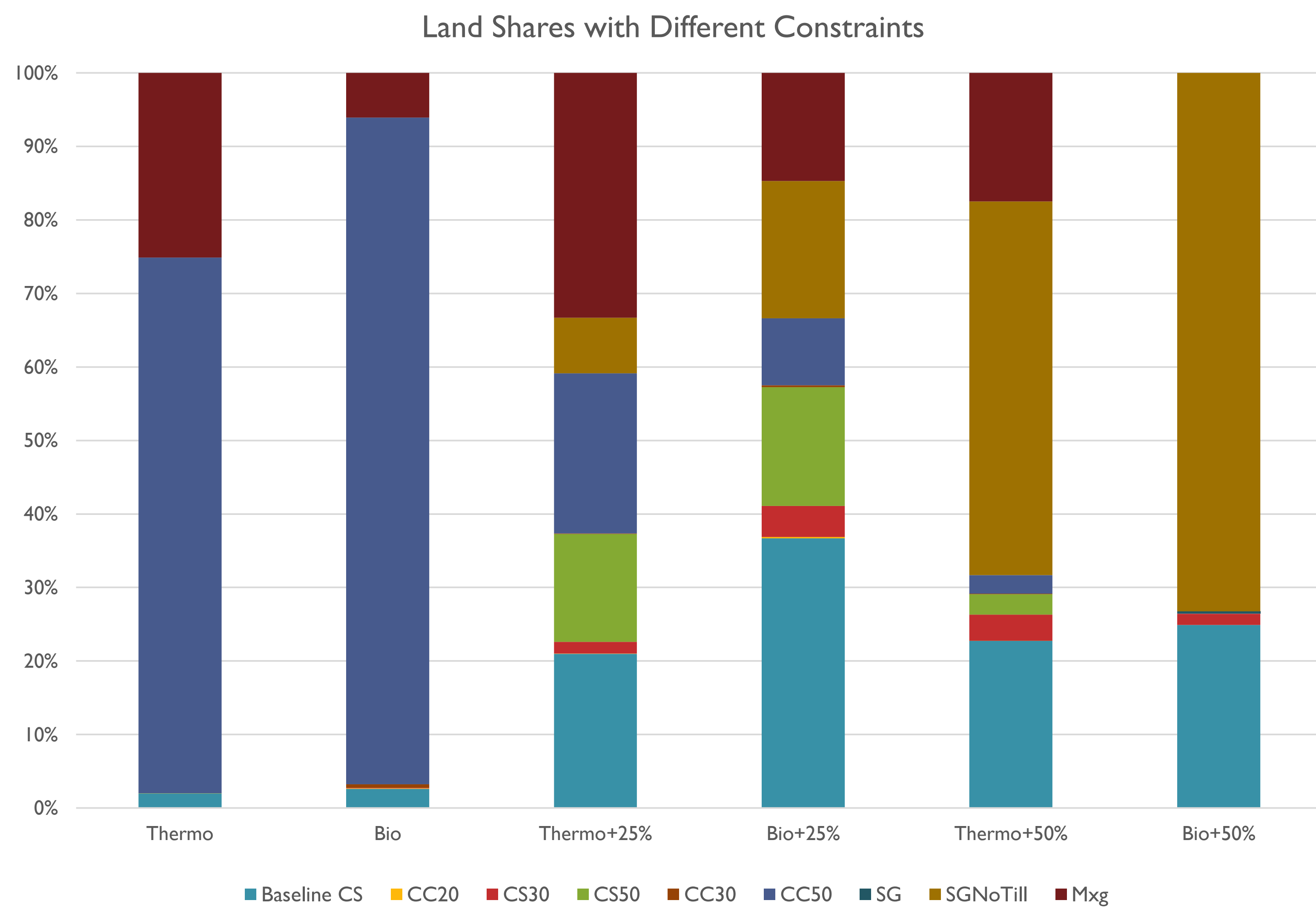
Biochemical biorefinery

- Total cost: $70,133,857
- Total biomass production: 858,483 metric tons per year
- CC50 (91%), Mxg (6%), baseline (3%)

Optimization Results with Pollutant Level Constraints

Pollutant Constraint	**25% Reduction Requirement**		**50% Reduction Requirement**	
	Thermochemical	Biochemical	Thermochemical	Biochemical
Cost ($)	141,532,768	94,475,733	161,532,738	145,285,324
Production (metric tons)	1,307,074	858,489	1,307,066	1,042,645
Total Nitrogen (% reduction)	-25%	-25%	-50%	-50%
Total Phosphorus (% reduction)	-25%	-25%	-63%	-80%
Sediment (% reduction)	-60%	-52%	-77%	-85%

MLSOPT Results with Different Constraints



Conclusions

- *Switchgrass and miscanthus*: highest biomass yields, higher costs

- *Corn stover*: economically least expensive, lower relative yield

- *Production requirement for thermochemical biorefinery*: perennial grasses required to supply from the watershed alone

- *Environmental protection and pollution control*: perennials are superior to corn stover

- *Implied Tradeoff* between cost of cellulosic feedstock & environmental improvement

THANK YOU

Q & A