GREAT LAKES BIOENERGY RESEARCH CENTER

Approaches for high resolution land use and bioenergy modeling

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Science Objectives

- GLBRC is the only DOE Bioenergy Center that contains sustainability research.
- **Objective 1.** Understand the environmental value and impact of alternative biofuel production systems, such that the ecosystem services associated with different systems can be quantified and used to construct tradeoff scenarios that can be subsequently used to identify the most appropriate systems for various physical and economic landscapes;
- **Objective 2.** Identify the social and economic incentives necessary for the adoption of cropping systems with the greatest environmental benefits in order to inform policy development.

Approach of GLBRC Sustainability Research

- Approximately 20% of GLBRC research funds devoted to sustainability.
- Systems approach with a landscape perspective is used to consider:
  - CO_2 stabilization, greenhouse gas (GHG) abatement,
  - wildlife habitat, biodiversity, pest protection,
  - ground and surface water protection, and flood control.
- Biogeochemistry modeling is combined with economic analysis and life-cycle analysis to complete these objectives.

Elements of GLBRC Sustainability Research

- Field trials at 2 locations (Kellogg, Arlington)
  - Grain based annual, Perennial, Novel systems.
- Improved Microbial-Plant interactions
- Biogeochemical responses
  - N2O, CH4, CO2 monitoring, full carbon accounting, water and nutrient balance
- Biodiversity responses
  - Plant and animal biodiversity – landscape scale
  - Microbial response in novel systems
- Socioeconomic response
- Modeling
  - Biogeochemical modeling, Life-cycle analysis (LCA), Integrated assessment analysis

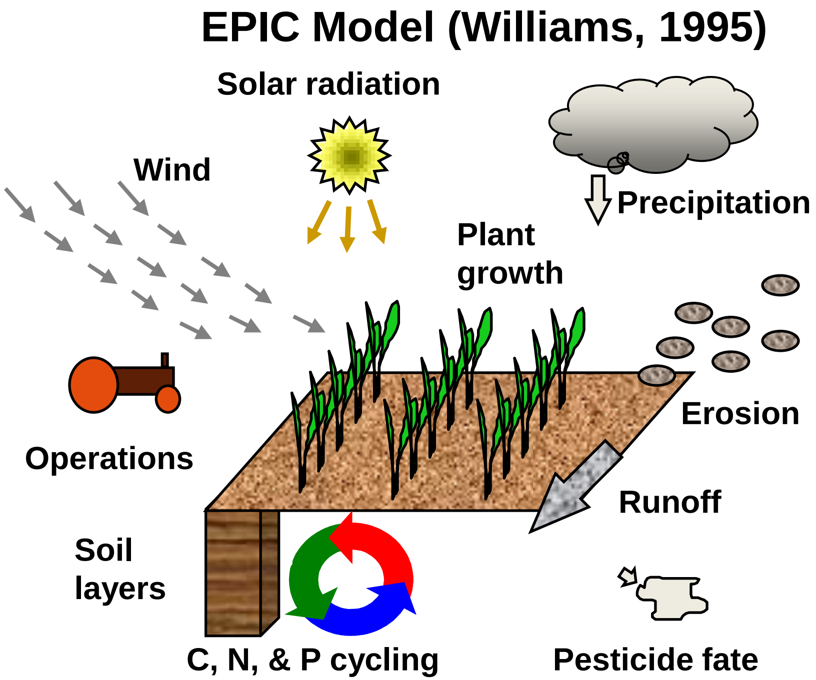
Biogeochemistry Modeling Objectives

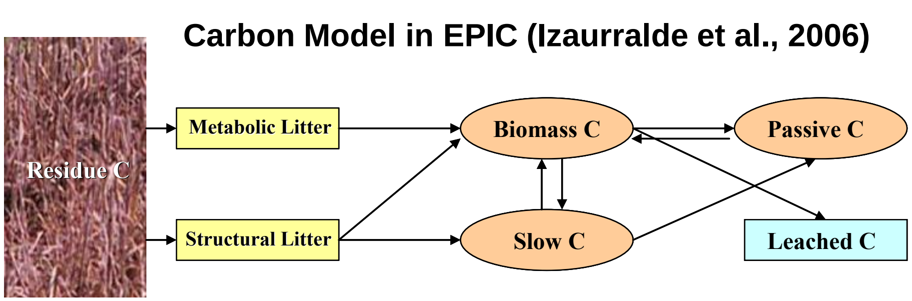
- Estimate crop yields using current and projected climate, soil conditions, management systems.
- Provide appropriate temporal and spatial scales, input design, and outputs for integration with economic analysis, life-cycle analysis (LCA), and biodiversity analyses .
- Provide additional sustainability information on:
  - Erosion, soil fertility,
  - Pesticide and nutrient leaching,
  - Production costs and net greenhouse gas emissions.

GLBRC Methodology

- Biogeochemical model (EPIC)
- Spatially-explicit data
  - Weather from DayMet (1km) or NLDAS (1/8 degree)
  - Land cover from Cropland Data Layer (CDL) (56 m)
  - Soils from SSURGO (1:12,000 – 1:63,000)
  - Land capability classification (LCC), based on SSURGO
- Land use and management
  - Designed to satisfy needs of economic, environmental and LCA analysis
  - Crop rotations (14), Tillage intensity (2), Residue treatments (2), Fertilizer level (2)
- Scaling
  - GLBRC plots at KBS and Arlington
  - Regional Intensive Modeling Areas (RIMAs) in Michigan and Wisconsin
  - 10-state North Central Region

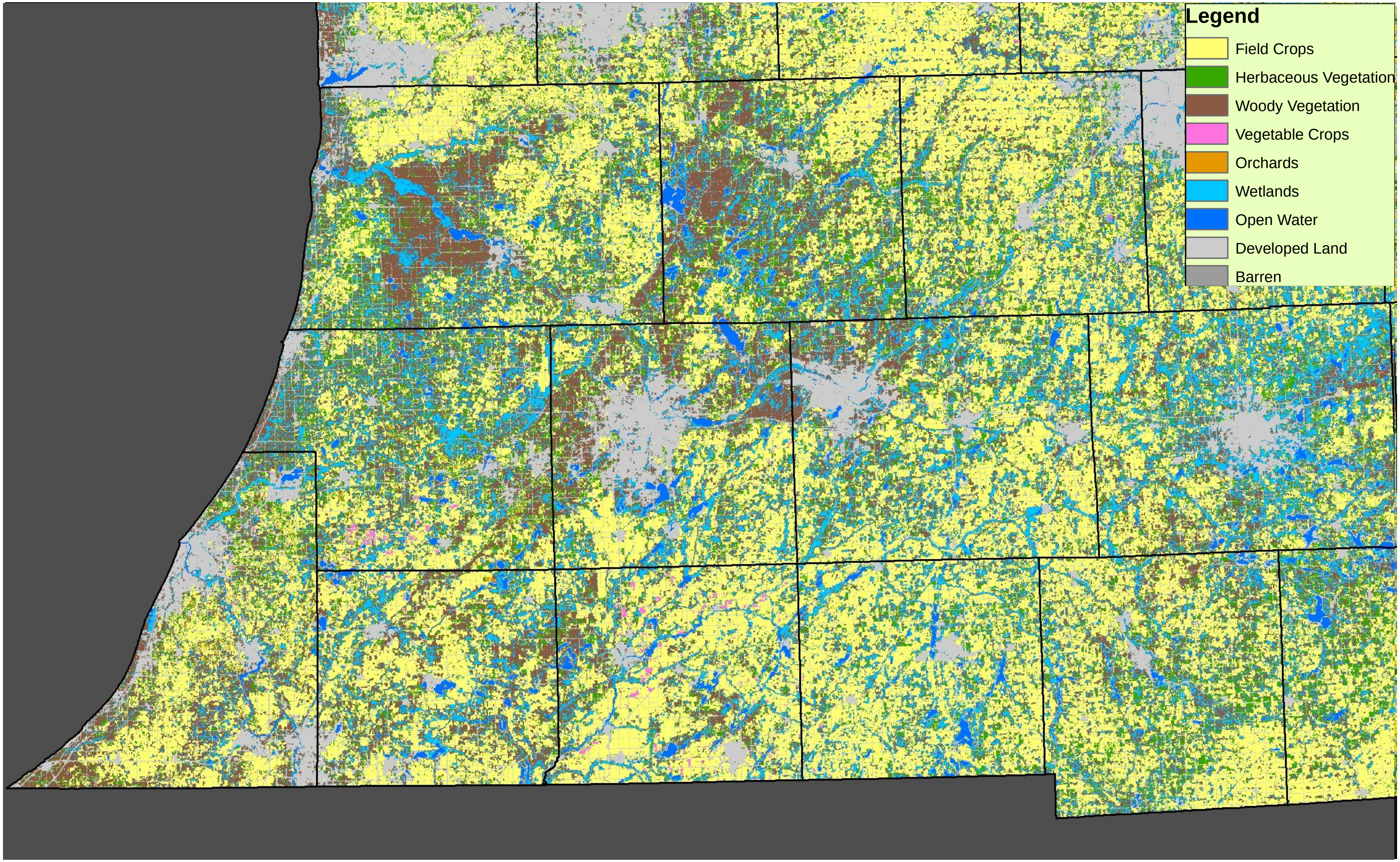
EPIC (Environmental Policy Integrated Climate): a comprehensive tool to model biophysical and biogeochemical processes as affected by climate, soil, and management interactions



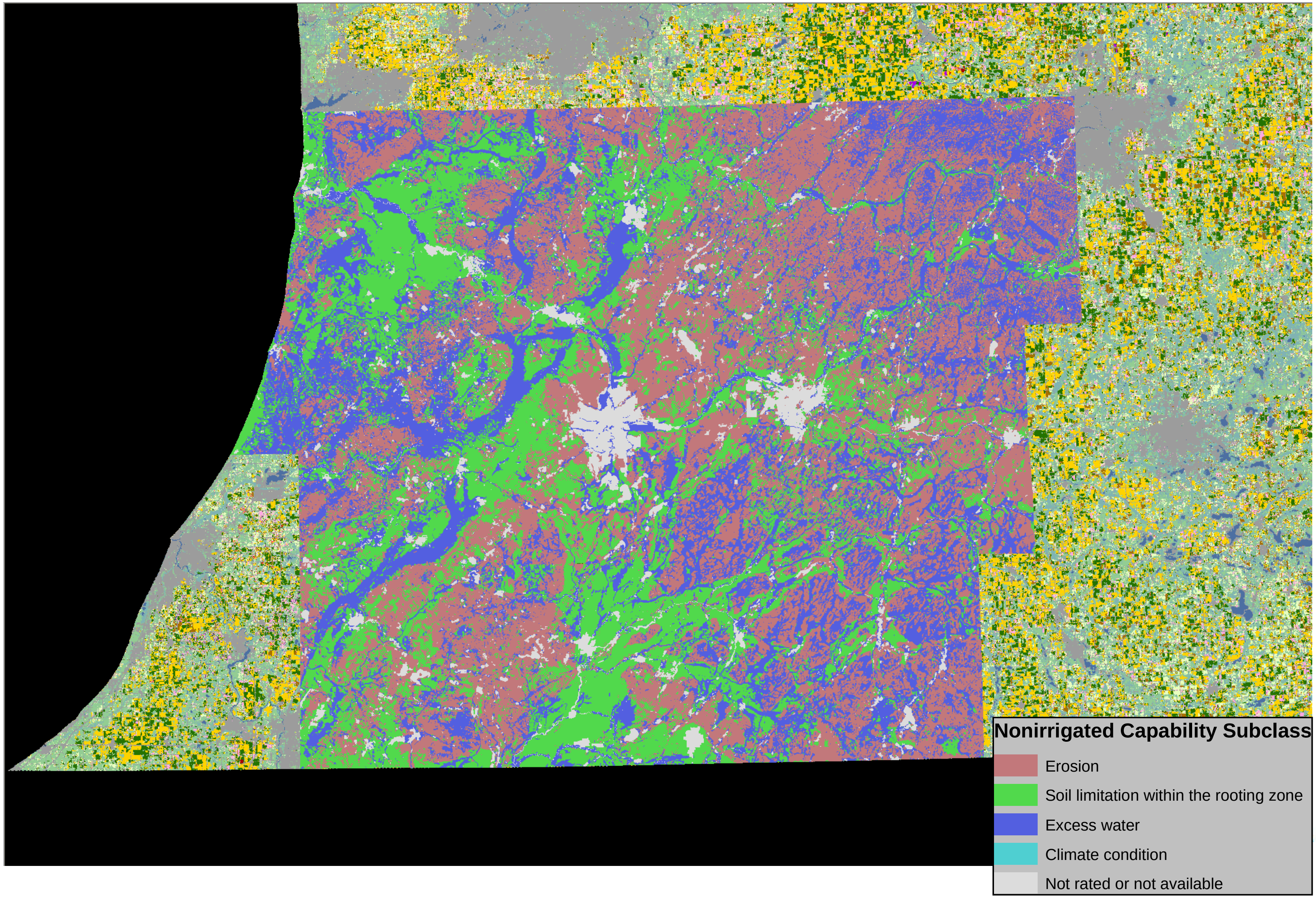


- Developed by USDA/JGCRI and maintained and Texas A&M University
- Required inputs
  - Weather: historical, climate projections
  - Crop rotation/management including tillage, fertilizer, irrigation, pesticide
  - Soil properties
- Key processes simulated:
- Plant growth and yield
  - Crops, grasses, trees
  - Complex rotations, intercropping, land use change
  - Radiation use efficiency
  - Plant stresses
- Water balance; irrigation, drainage
- Heat balance; soil temperature
- Carbon cycling, including eroded carbon
- Nitrogen cycling
- Erosion by wind and water
- Carbon emissions coefficients

Michigan RIMA: 2007 Crop Data Layer



Soil Distribution in Michigan RIMA



Weather Data

- Requirements
  - Daily
  - Max/Min Temperature, Precipitation, Radiation, Relative Humidity
- Sources
  - DayMet – daily, 1km, 1980-2008
  - NLDAS – 1 hour, 1/8 degree, 1979-present

LCA and economic treatments for RIMAs

Crop rotation	Rotation phases	Tillage level	Yield goal	Fertilizer levels	Residue removal	Cover crop	No. Combinations
Continuous corn	1	2	2	3	2	2	48
Corn-soybean	2	3	2	3	2	2	144
Corn-soybean-wheat	3	2	2	3	2	2	144
Corn-soybean-canola	3	2	2	3	2	2	144
Corn-corn-soybean-wheat	4	2	2	3	2	2	192
Alfalfa-alfalfa-alfalfa-corn-corn-soybean	3	2	3	3	2	2	216
Switchgrass				4			4
Miscanthus				2			2
Grass mix				3			3
Poplar				3			3
Old field				3			3
Native prairie (warm season)				3			3
Native prairie (cold season)				3			3
Total							909

The challenge…

- Number of simulation runs could be huge given number of treatments and number of map units in each RIMA
- Thus, we need to explore how to aggregate the spatial units but retain the spatial information to map back the results

epic.dat

FSITE	SITECOM.DAT
FWPM1	WPM1US.DAT
FWPM5	WPM5US.DAT
FWIND	WINDUS.DAT
FWIDX	WIDXCOM.DAT
FCROP	CROPCOM.DAT
FTILL	TILLCOM.DAT
FPEST	PESTCOM.DAT
FFERT	FERTCOM.DAT
FSOIL	SOILCOM.DAT
FOPSC	OPSCCOM.DAT
FTR55	TR55COM.DAT
FPARM	PARM0810.DAT
FMLRN	MLRN0810.DAT
FPRNT	PRNT0810.DAT
FCMOD	CMOD0810.DAT
FWLST	WDLSTCOM.DAT

Current Approach to EPIC Simulations

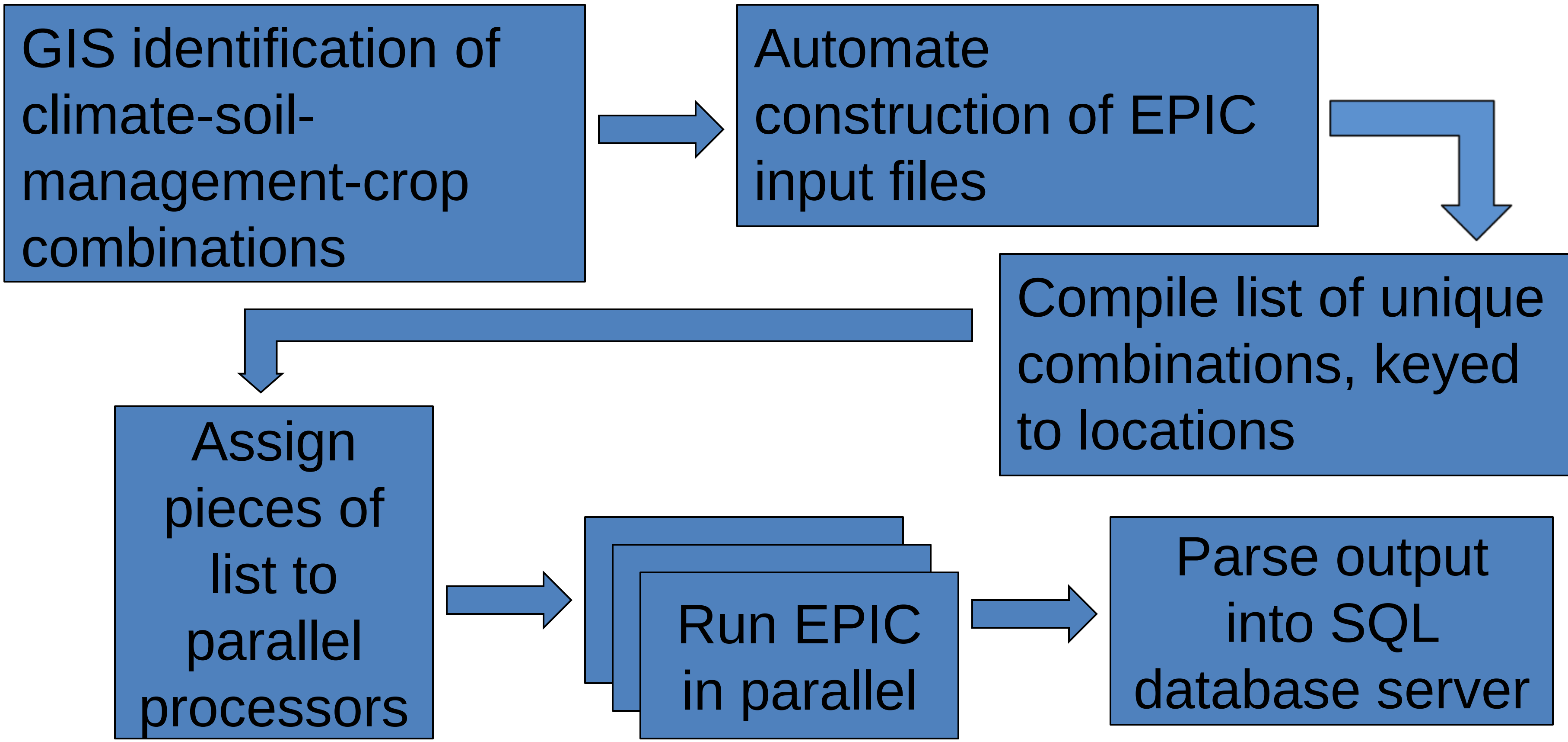
Existing Tools:

- iEPIC
- WinEPIC

CPU Requirements for Michigan RIMA

- 74 crop x management combinations
- Weather zones – 1+ per county
- ~750 soil series soil map units
- ~1 million EPIC simulations
- 24 simulation years, each year taking 1 second
- = 7,000 hours computer time or 287 days

High Performance Computing Approach to EPIC Simulations



HPC Calculation

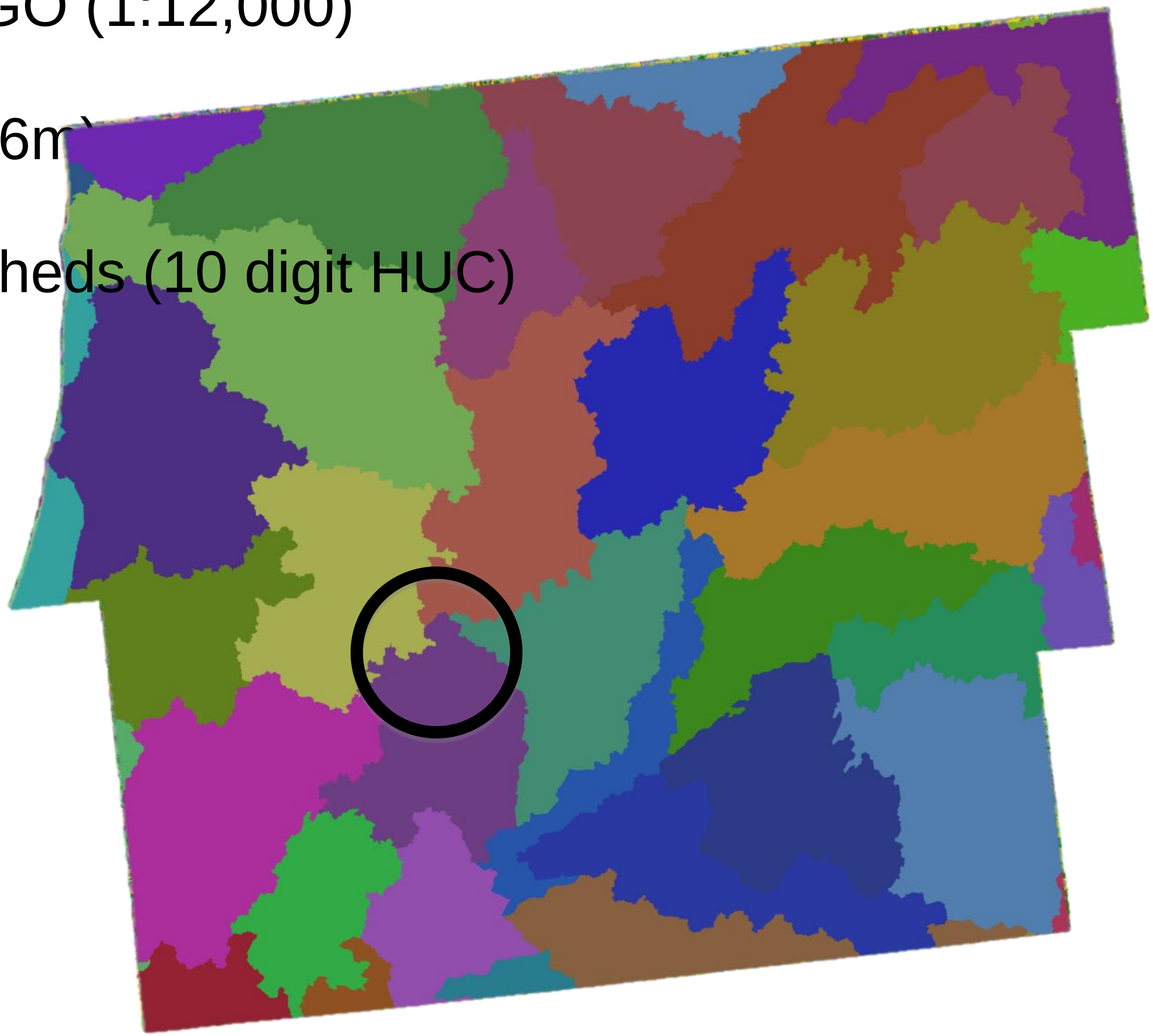
- Optimized code on Linux, 24 Simulation Years ~ 6 seconds. Gain of 4x.
- Automated creation of self-contained packages that can be executed simultaneously on ORNL Cluster.
- Result 287 days of compute time completed in ~1 day.
- Automated extraction and cataloging of results.
- Complete process is automatable.

Use of GIS

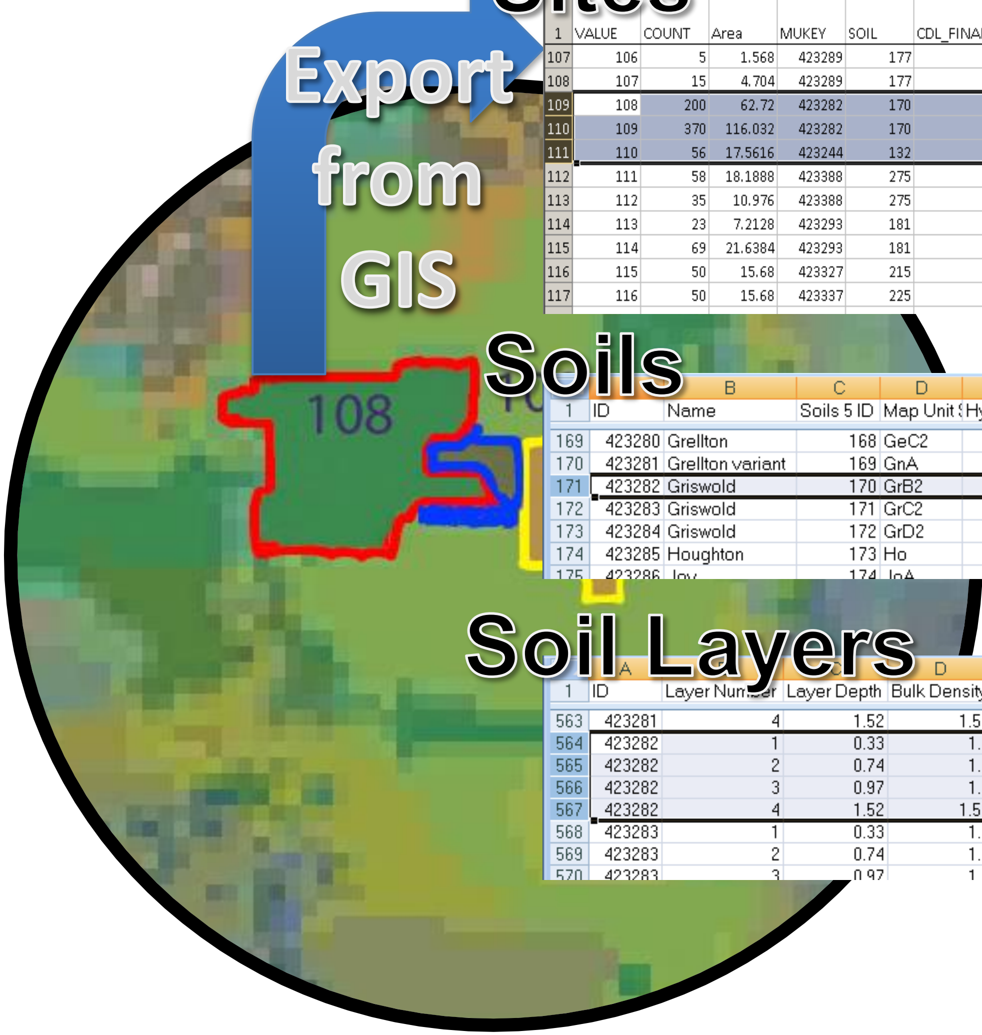
L1: SSURGO (1:12,000)

L2: CDL (56m)

L3: Watersheds (10 digit HUC)



HSMUs and Data from GIS



Sites

1	VALUE	COUNT	Area	MUKEY	SOIL	CDL_FINAL	Long	Lat	Elev	COUNTY	Slope	Sloplen	LC	SLC	LandUse	10-digit
107	106	5	1.568	423289	177	3	-89.0476	43.6083	261.62	Columbia County	9	46	3	e	woody vegetation	403020105
108	107	15	4.704	423289	177	1	-89.0476	43.6083	261.62	Columbia County	9	46	3	e	field crops	403020105
109	108	200	62.72	423282	170	2	-89.0476	43.6083	261.62	Columbia County	4	61	2	e	herbaceous vegetati	403020105
110	109	370	116.032	423282	170	1	-89.0476	43.6083	261.62	Columbia County	4	61	2	e	field crops	403020105
111	110	56	17.5616	423244	132	1	-89.0476	43.6083	261.62	Columbia County	1	76	3	w	field crops	403020105
112	111	58	18.1888	423388	275	2	-89.0476	43.6083	261.62	Columbia County	9	46	4	e	herbaceous vegetati	403020105
113	112	35	10.976	423388	275	1	-89.0476	43.6083	261.62	Columbia County	9	46	4	e	field crops	403020105
114	113	23	7.2128	423293	181	1	-89.0476	43.6083	261.62	Columbia County	16	30	4	e	field crops	403020105
115	114	69	21.6384	423293	181	2	-89.0476	43.6083	261.62	Columbia County	16	30	4	e	herbaceous vegetati	403020105
116	115	50	15.68	423327	215	3	-89.0476	43.6083	261.62	Columbia County	9	46	6	s	woody vegetation	403020105
117	116	50	15.68	423337	225	3	-89.1447	43.609	272.22	Columbia County	9	46	4	e	woody vegetation	403020101

Soils

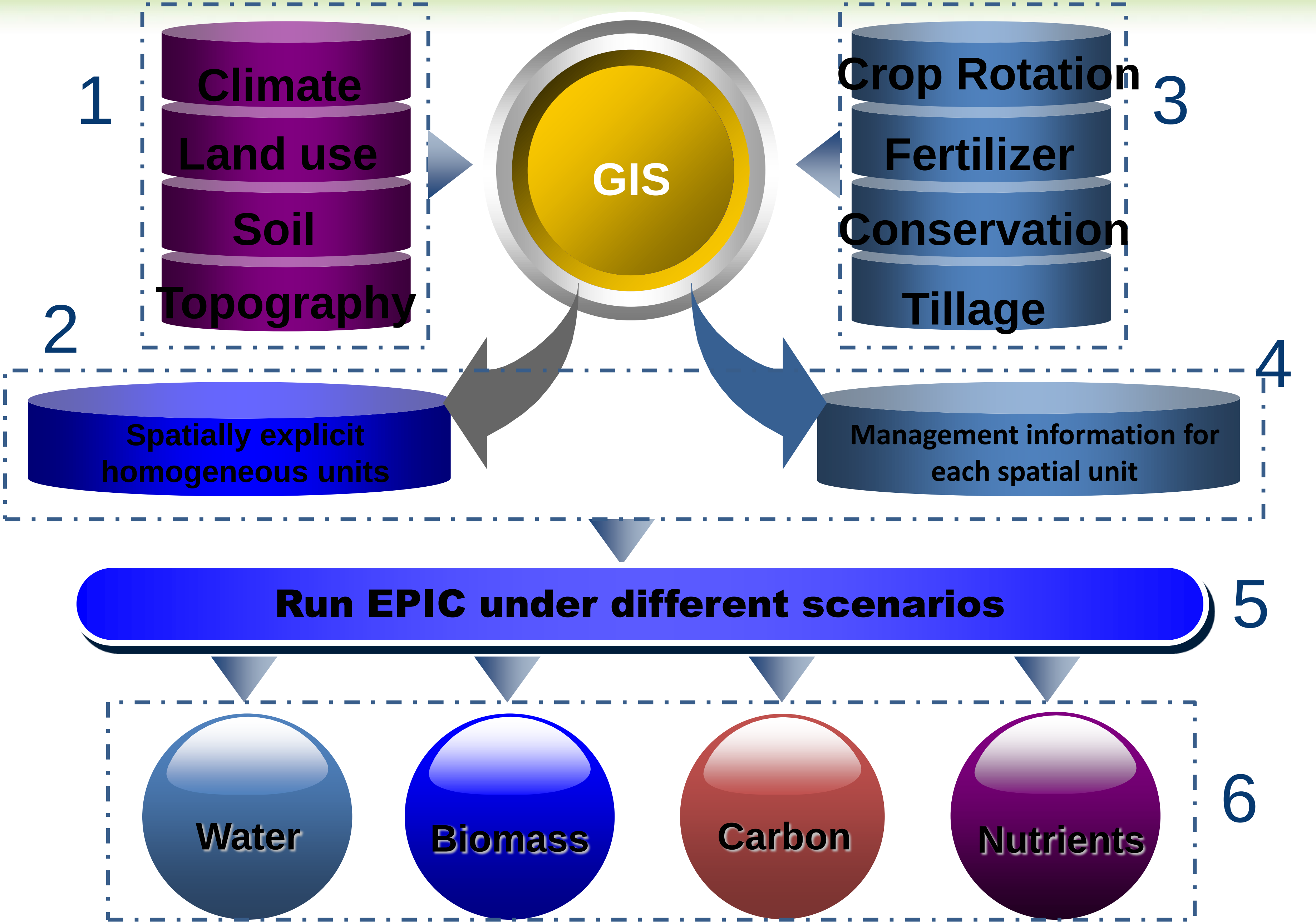
1	ID	Name	Soils 5 ID	Map Unit S	Hydrologic	Number	Albedo	Previous Years Cultivation	Maximum Number of Layers	Initial Splitting Thickne
169	423280	Grellton	168	GeC2	2	5	0.1875	100	6	
170	423281	Grellton variant	169	GnA	2	4	0.1	100	5	
171	423282	Griswold	170	GrB2	2	4	0.125	100	5	
172	423283	Griswold	171	GrC2	2	4	0.125	100	5	
173	423284	Griswold	172	GrD2	2	4	0.125	100	5	
174	423285	Houghton	173	Ho	1	2	0.1	100	3	
175	423286	Joy	174	JoA	2	3	0.1	100	4	

Soil Layers

1	ID	Layer Number	Layer Depth	Bulk Density	Wilting Point	Field Capacity	Sand Content	Silt Content	Organic Carbon	pH	Organic N Concentratic
563	423281	4	1.52	1.58	12.6	28	26.5	53.5	0.145	6.5	
564	423282	1	0.33	1.2	12.8	27.9	26.5	53.5	1.74	6.7	
565	423282	2	0.74	1.3	13.5	27.9	38	36	0.29	6.7	
566	423282	3	0.97	1.5	10.8	19.1	65.1	14.9	0.058	6.7	
567	423282	4	1.52	1.55	9.7	18.2	67.2	15.3	0.029	7.9	
568	423283	1	0.33	1.2	12.8	27.9	26.5	53.5	1.74	6.7	
569	423283	2	0.74	1.3	13.5	27.9	38	36	0.29	6.7	
570	423283	3	0.97	1.5	10.8	19.1	65.1	14.9	0.058	6.7	

GIS Integration

- HSMU Generation facilitated by GIS
- Intersections of layers produce the large numbers of sites
- All CDL types: crops, forests, fields
- About 4 Hours to Build for a Region
- About 4 Hours to Filter Data from GIS and prepare EPIC Input Files
- Automatable through PostGIS

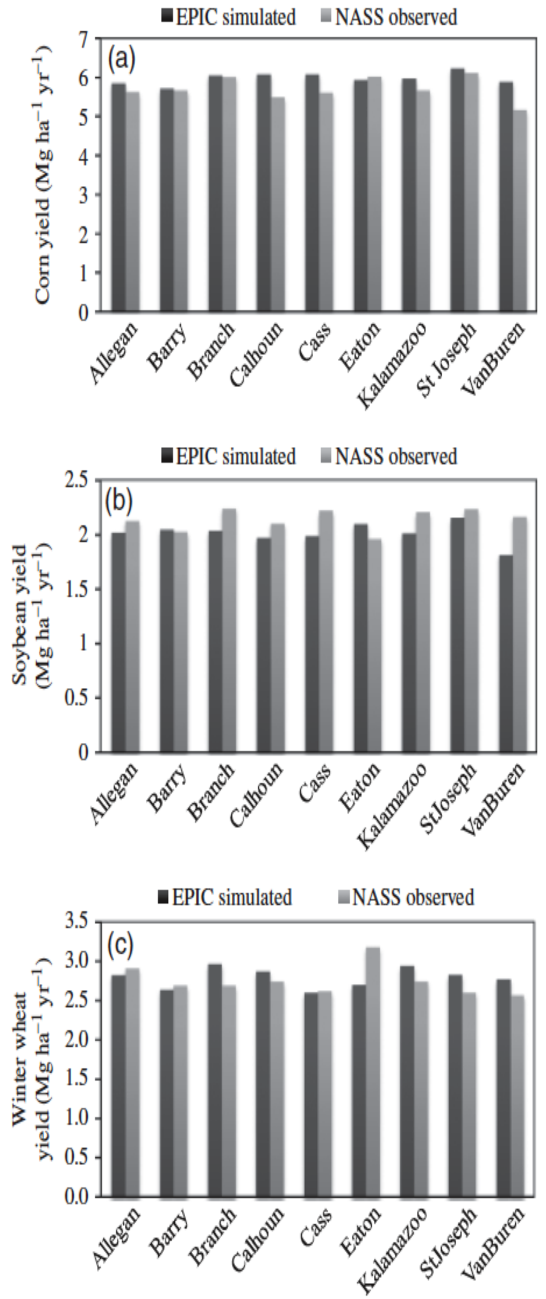

1
Climate
Land use
Soil
Topography
GIS
3
Crop Rotation
Fertilizer
Conservation
Tillage
2
Spatially explicit homogeneous units
4
Management information for each spatial unit
Run EPIC under different scenarios
5
Water
Biomass
Carbon
Nutrients
6

Michigan RIMA simulations

Simulation scenarios and output

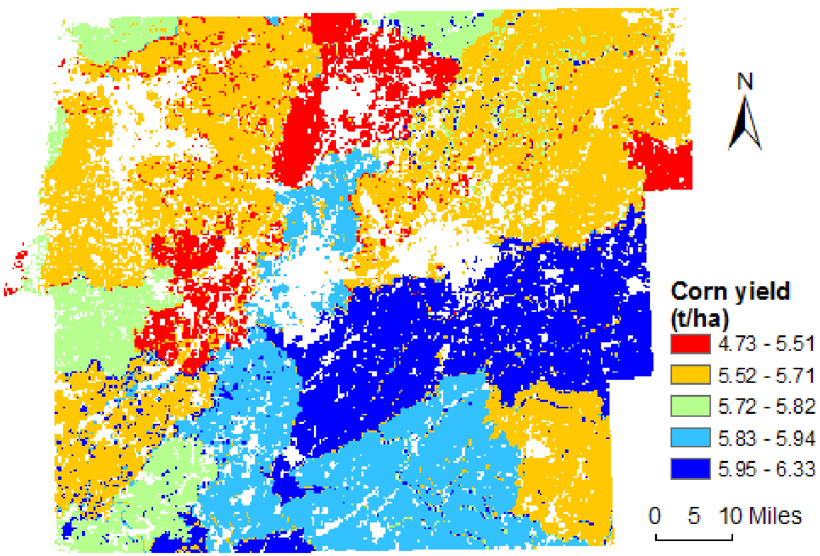
- Simulated 74 scenarios
  - Annual and perennial, with and without cover crops
  - Continuous or in a rotation
  - Different fertilizer/pesticide input levels
  - Tillage levels
  - With or without residue removal
- Model output
  - Plant yield (grain, seed, residue, biomass)
  - Soil erosion
  - Water balance
  - Carbon balance, including eroded carbon
  - Nitrogen losses, including leaching and N_2O

EPIC Model Validation

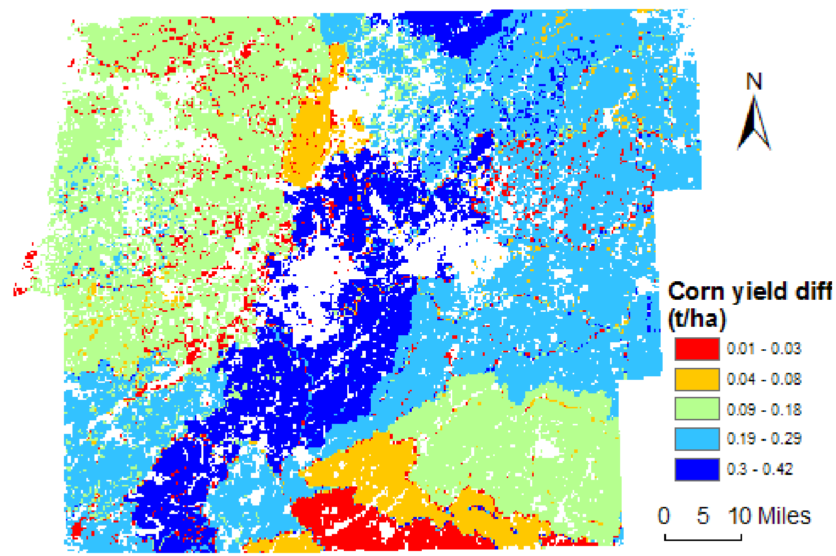


Example of spatially-explicit simulations for Michigan RIMA

Average corn yield (Mg ha^{-1}) with conventional tillage

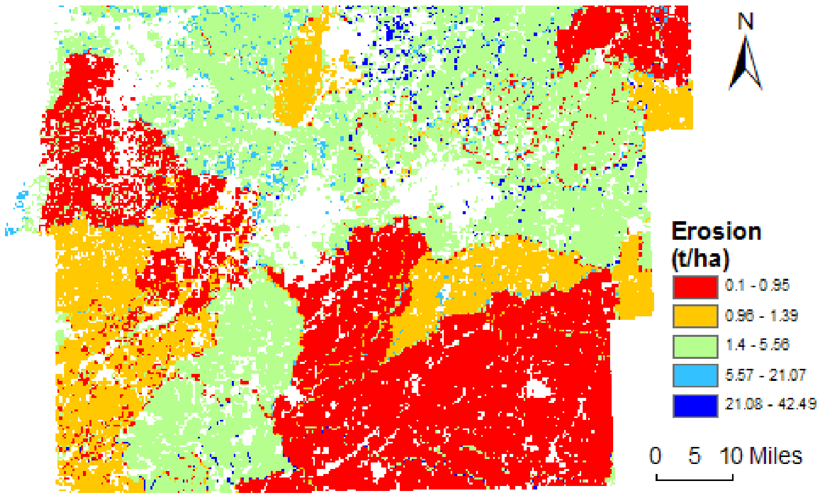


Difference in corn yield (Mg ha^{-1}) due to residue removal

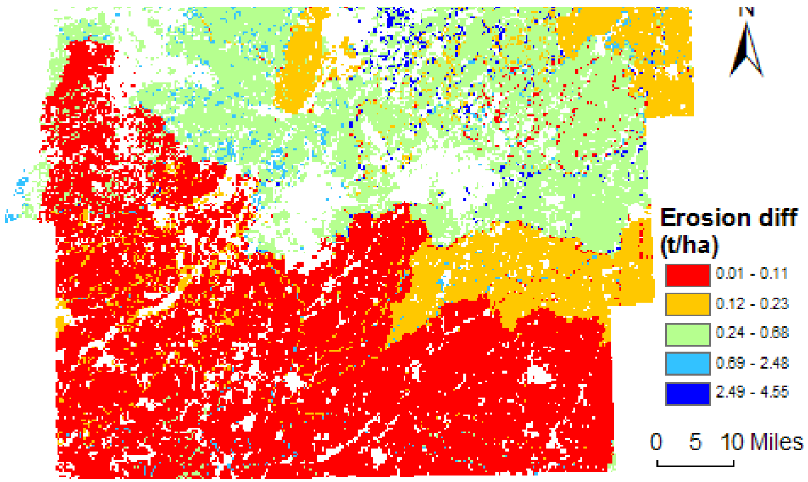


Example of spatially-explicit simulations for Michigan RIMA (cont'd)

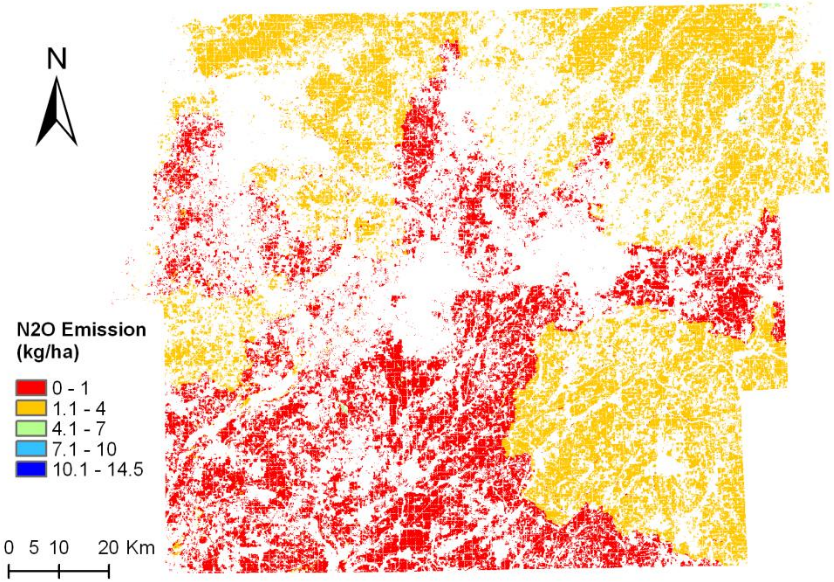
Average annual soil erosion (Mg ha^{-1} yr^{-1}) in conventional till corn



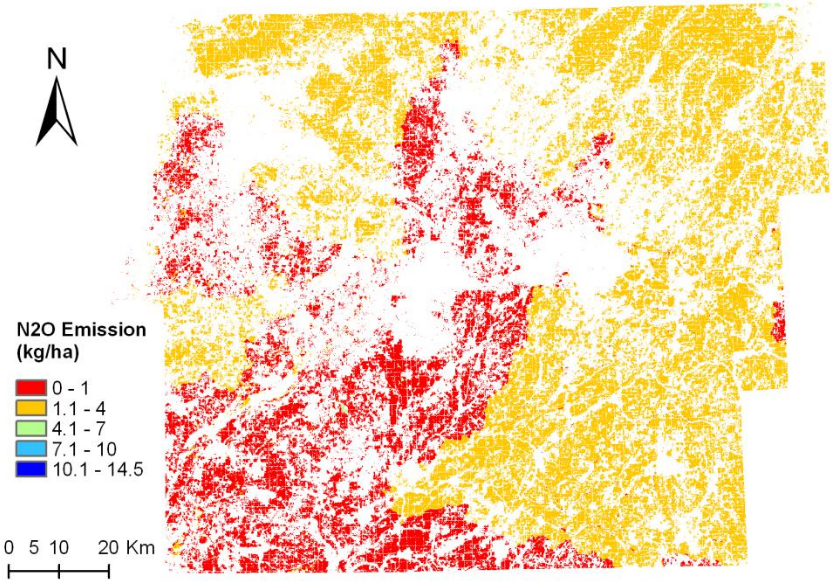
Difference in soil erosion (Mg ha^{-1} yr^{-1}) in conventional till corn due to corn residue removal



Spatially-Explicit Simulations of N_2O fluxes in SW Michigan



Corn-soybean, chisel tillage, 125 Kg N, no residue removed

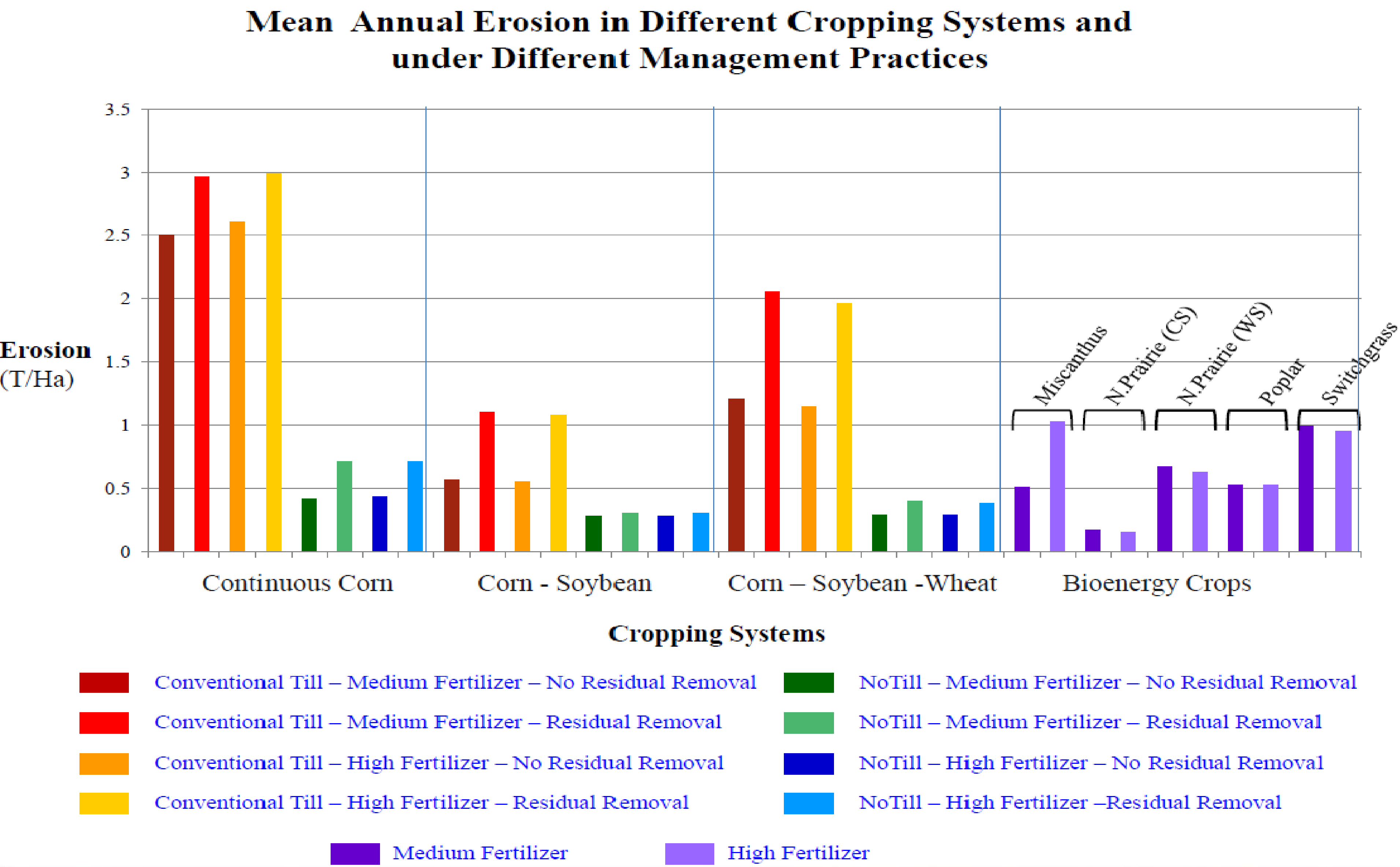


Corn-soybean, chisel tillage, 125 Kg N, residue removal

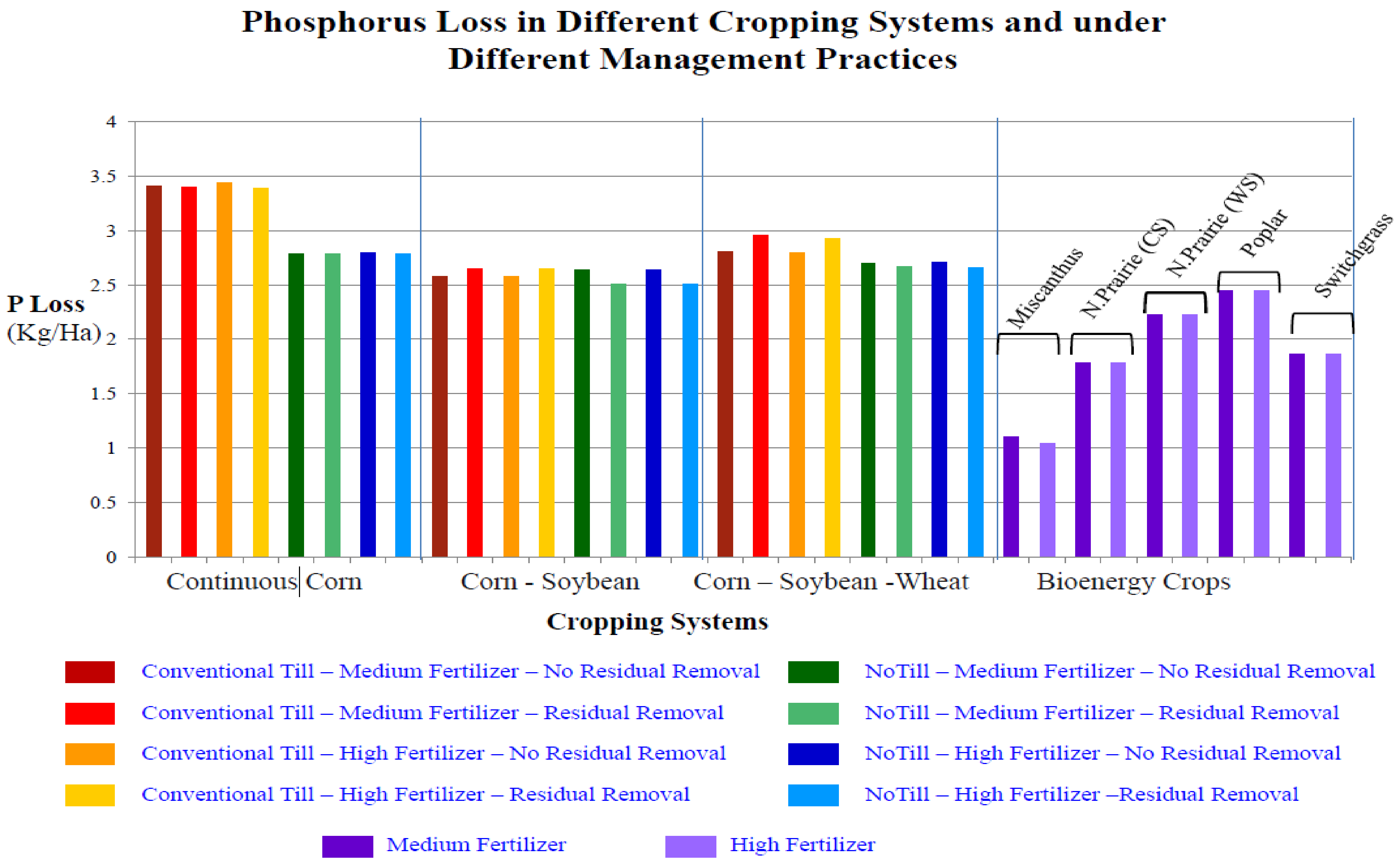
Simulated bioenergy production under various bioenergy treatments

Cropping system	Bioenergy (GJ ha^{-1} y^{-1})
Alfalfa – corn	269
Continuous corn	181
Corn – soybean	185
Corn – soybean – canola	197
Corn – soybean – wheat	243
Grass mix	187
Miscanthus	252
Native prairie	117
Poplar	49
Switchgrass	181

Environment and Sustainability Assessment Using EPIC - Erosion



Environment and Sustainability Assessment Using EPIC – P Loss



Environment and Sustainability Assessment Using EPIC – N_2O

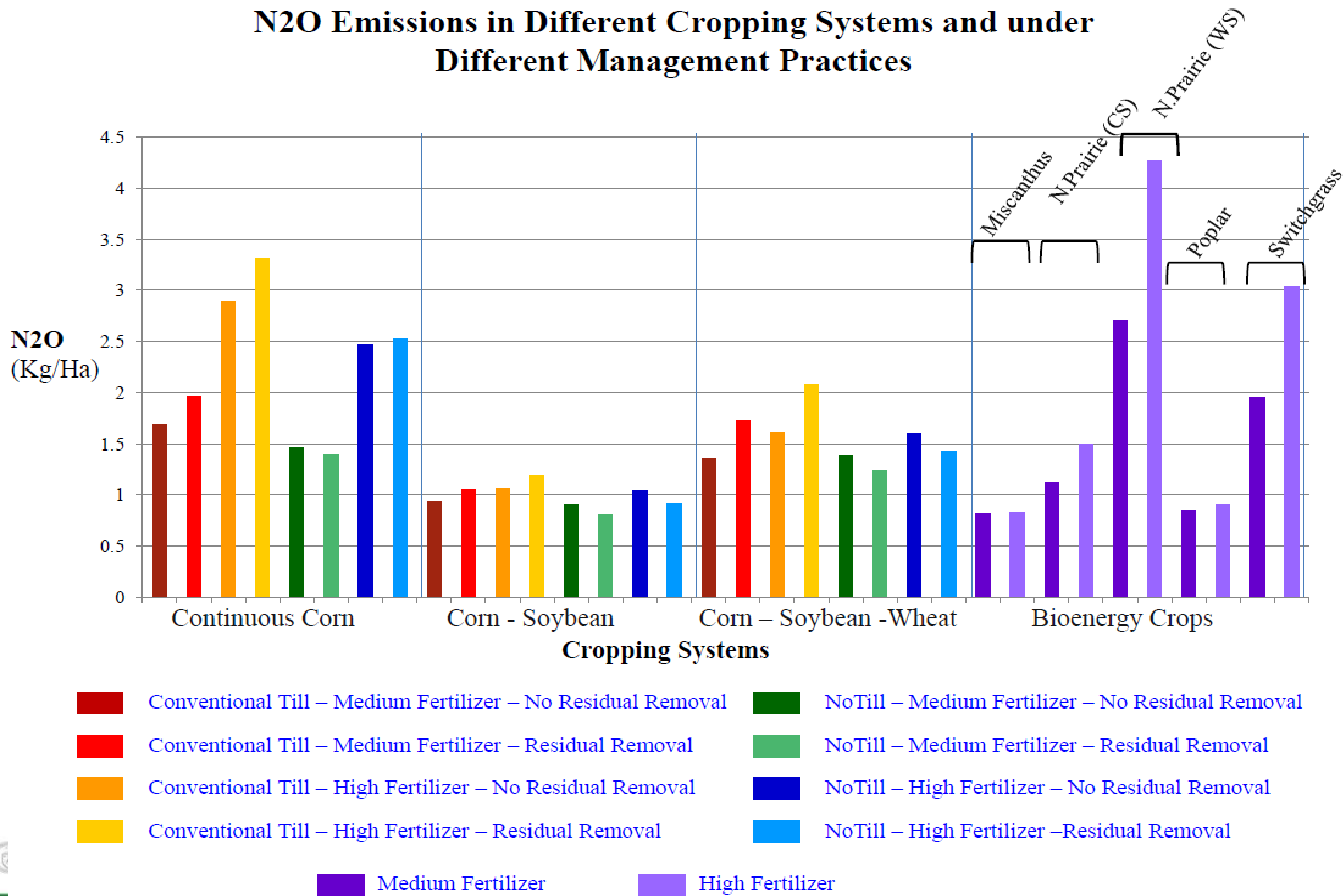
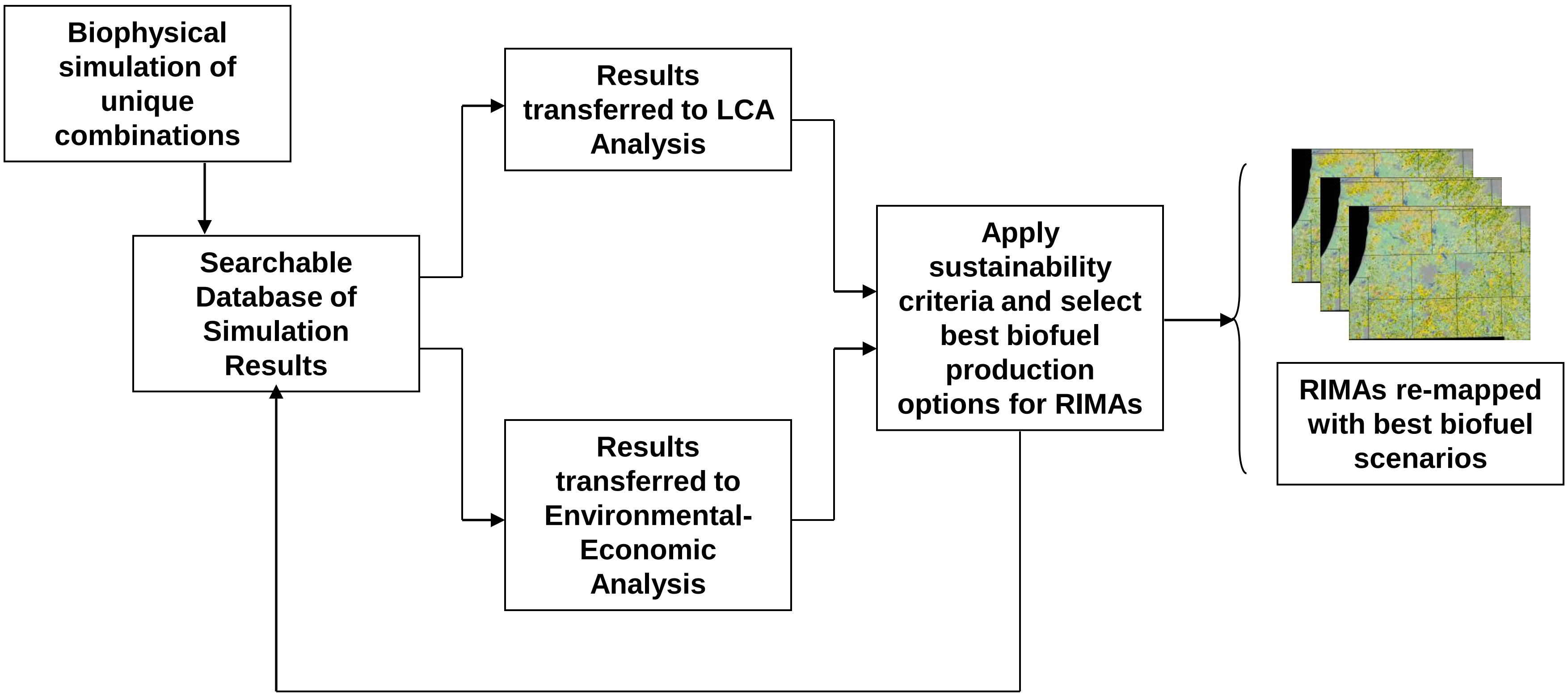


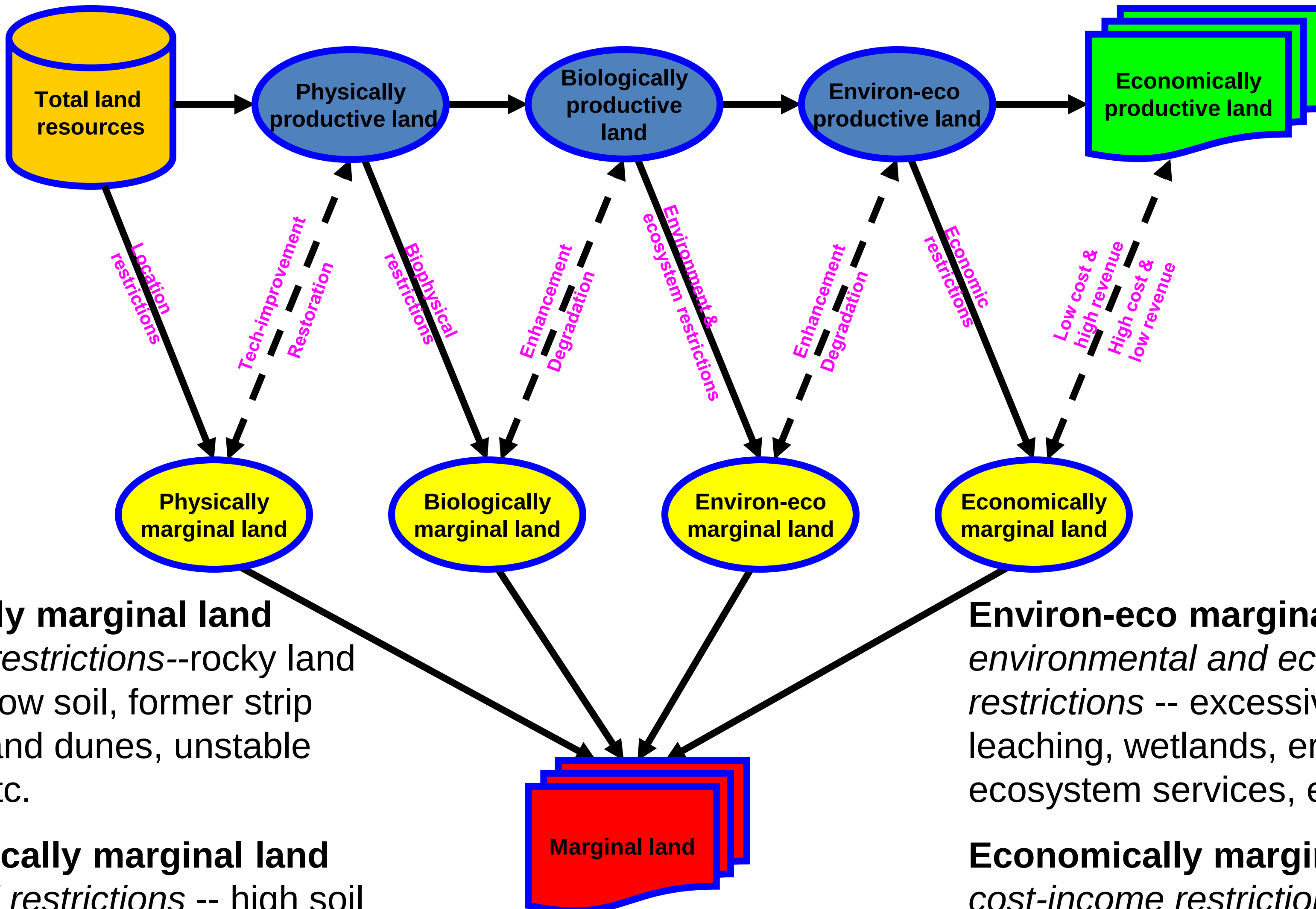
Diagram of information flow and integration of biophysical, LCA, environmental-economic, and sustainability analyses of biofuel production in the Michigan and Wisconsin RIMAs



Future Scenarios

- Climate change impacts
- Utilization of marginal land
- Biodiversity considerations

Hierarchy of Marginal Land



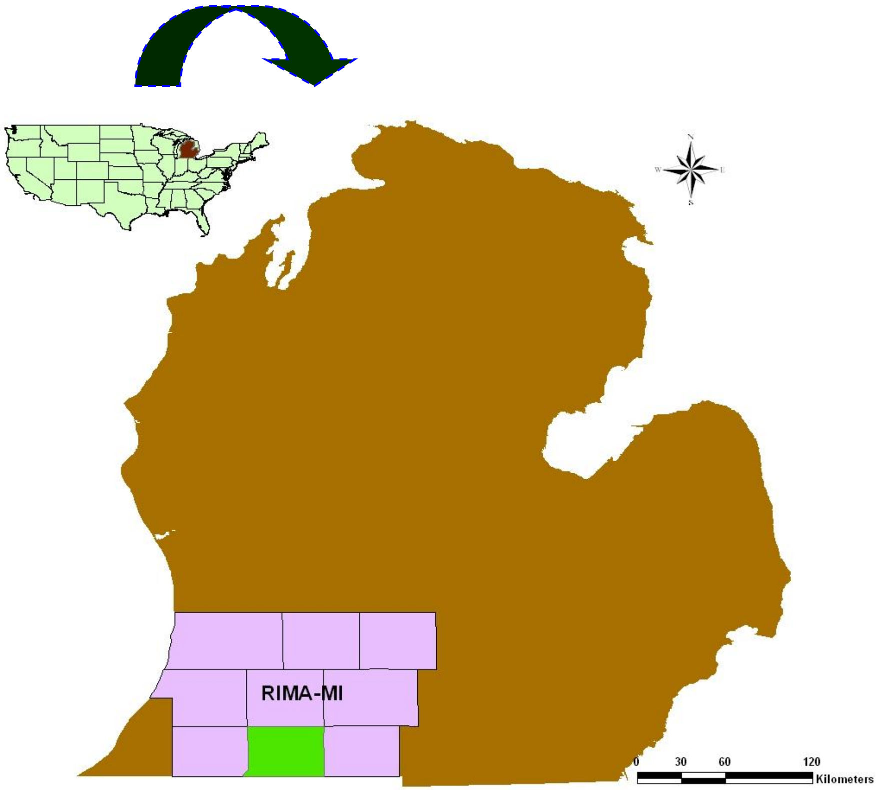
Physically marginal land
physical restrictions--rocky land with shallow soil, former strip mines, sand dunes, unstable slopes, etc.

Biophysically marginal land
biological restrictions -- high soil loss, low fertility, pH, saline soils etc.

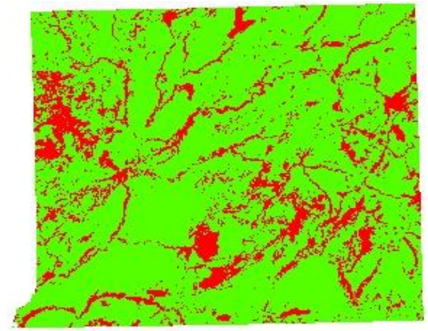
Environ-eco marginal land
environmental and ecological restrictions -- excessive nitrate leaching, wetlands, erosion or ecosystem services, etc.

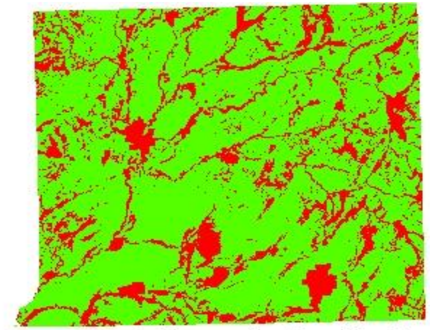
Economically marginal land
cost-income restrictions – breakeven prices.

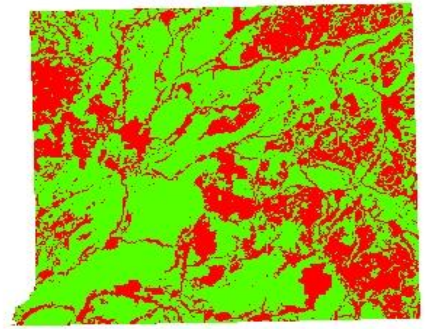
Marginal Land Classification Test

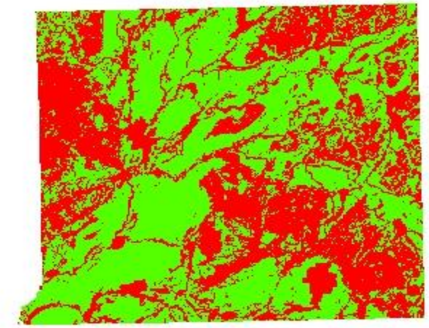


St. Joseph County in RIMA of Michigan as an example of hierarchical marginal land classification

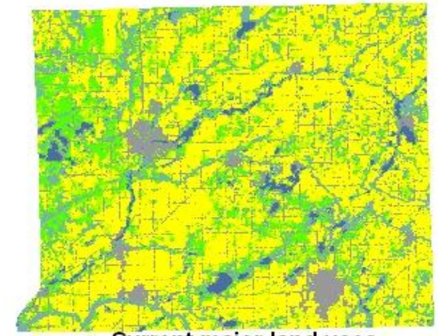

Marginal land -(land capability class>3)


Physically marginal-land (red)


Biologically marginal-land (red)


Envrion-eco marginal-land (red)

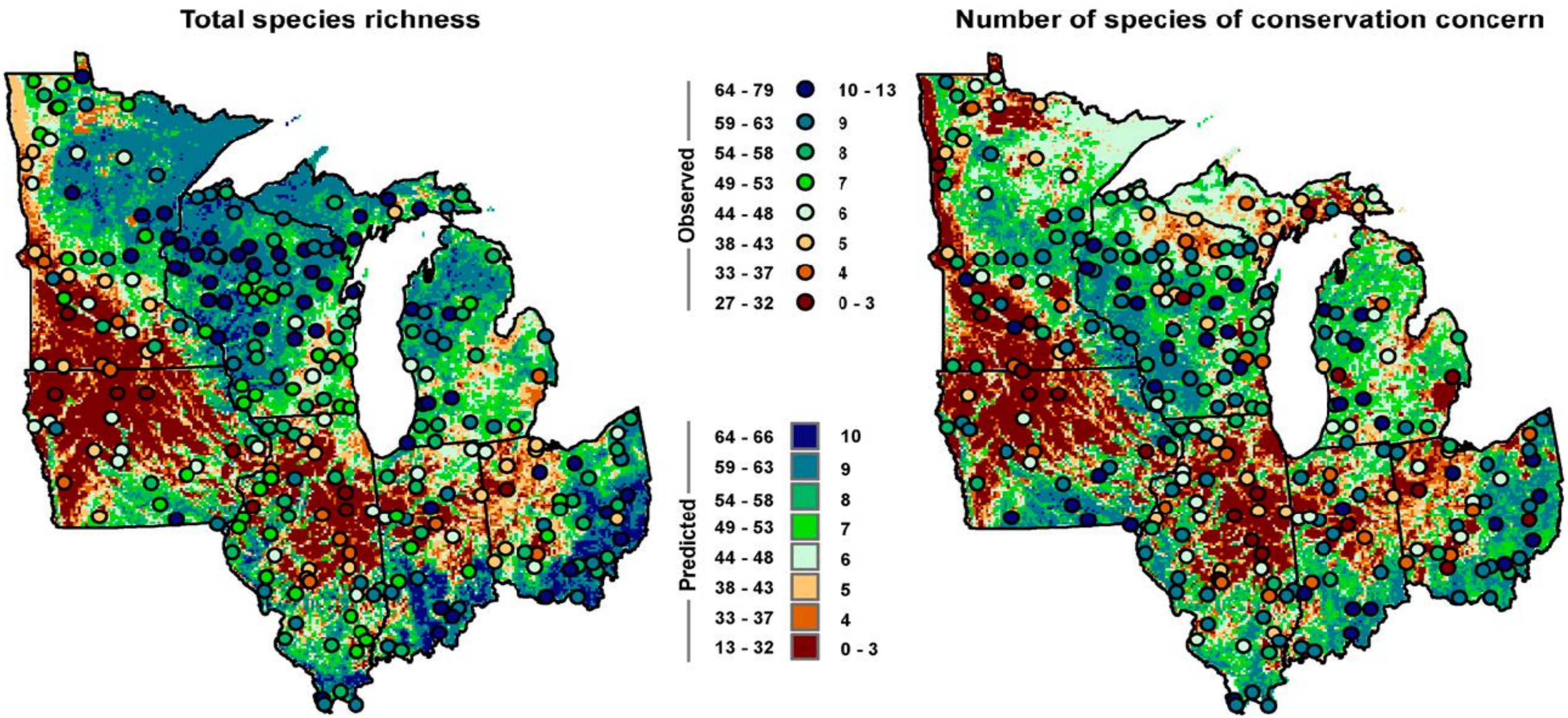

Economic marginal-land (red)


Current major land uses (yello-crop, green-tree, gray-urban)

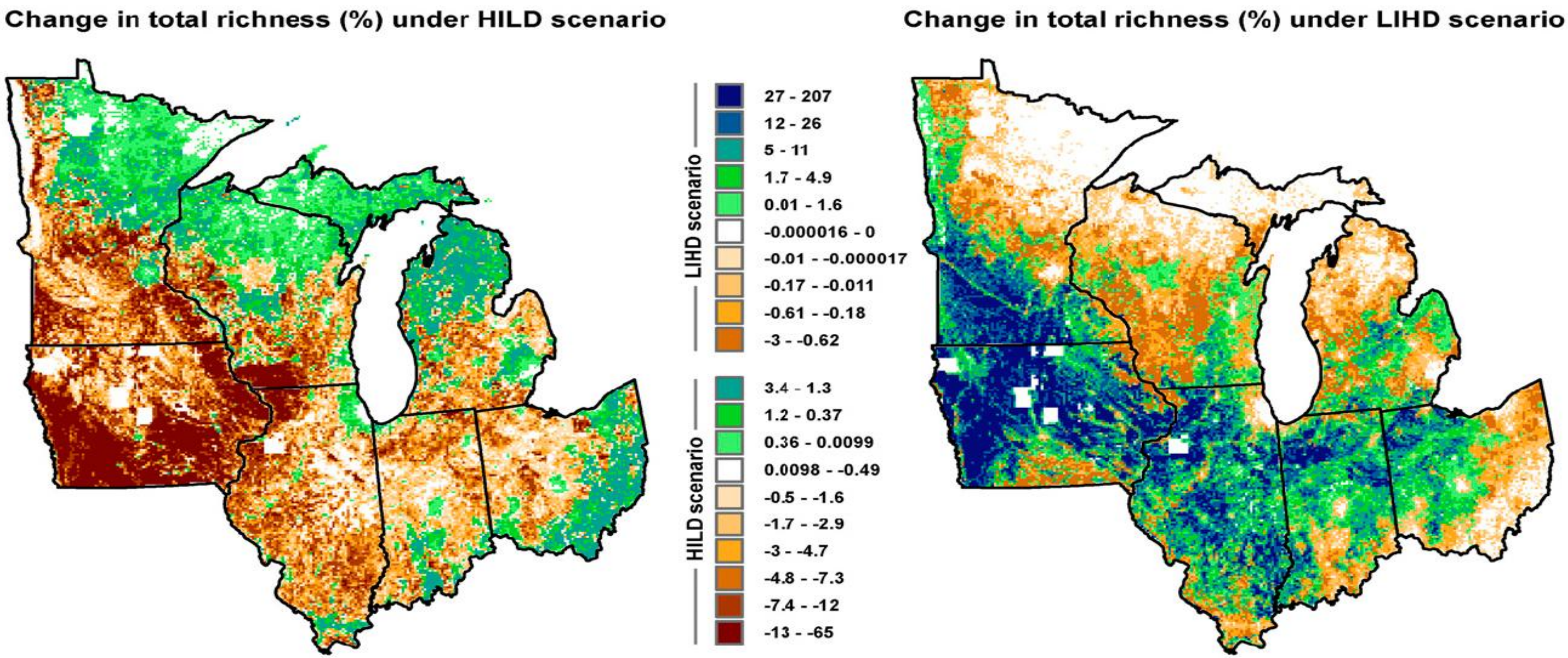
Biodiversity

Changes in landscape-scale bird species richness in the Upper Midwest

- Meehan et al., 2010 – PNAS



Bird Species Richness under Divergent Bioenergy Scenarios



High-input low-diversity (HILD)
9.5 million ha of marginal land that currently contain LIHD habitats were converted to HILD bioenergy crops.

Low-input high-diversity (LIHD)
8.3 million ha of marginal land that currently contain HILD crops were converted to LIHD habitats.

Summary

- Long-term sustainability of the underlying production is key to the success of a biofuel economy.
- Consequences of a biofuel economy could be positive or negative with regard to sustainability and environmental impact.
- An integrated systems approach that considers landscapes is required for a full analysis.
- An ability to complete analyses at high spatial and temporal resolution is crucial.

Summary (Continued)

- Automation of front end and back end of EPIC simulations is required to provide information at needed spatial detail
  - Streamline preparation of EPIC inputs
  - Allows parallel computation
  - Results in full EPIC output availability in searchable database server – temporally and spatially explicit
- The GLBRC methodology takes advantage of spatially-explicit databases to
  - Accommodate simulation of numerous agricultural food and biofuel production systems
  - Identify location of “marginal lands”
  - Create spatially-explicit scenarios of landscape configurations for biofuel production