Linking Externalities from the Land to their Consequences in the Sea: A Model of Land Use, Costs, Hydrology and the Gulf of Mexico Hypoxic Zone

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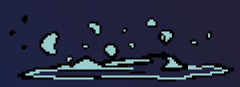

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Outline

I. Overview of Hypoxic zones in coastal systems

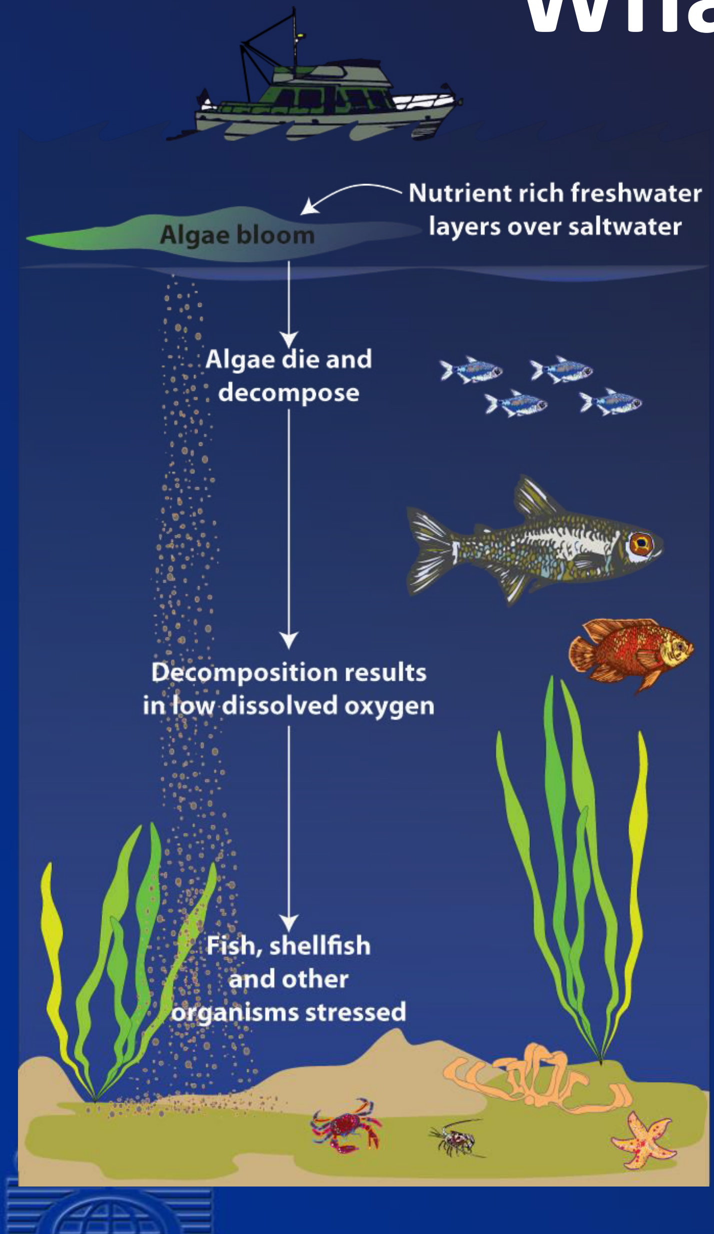
II. The Hypoxic Zone in the Gulf of Mexico

III. Integrated Modeling of the Gulf and Hypoxic Zone

IV. Findings: Costs of Achieving Reductions in Zone

V. Final remarks and caveats galore

What is hypoxia?



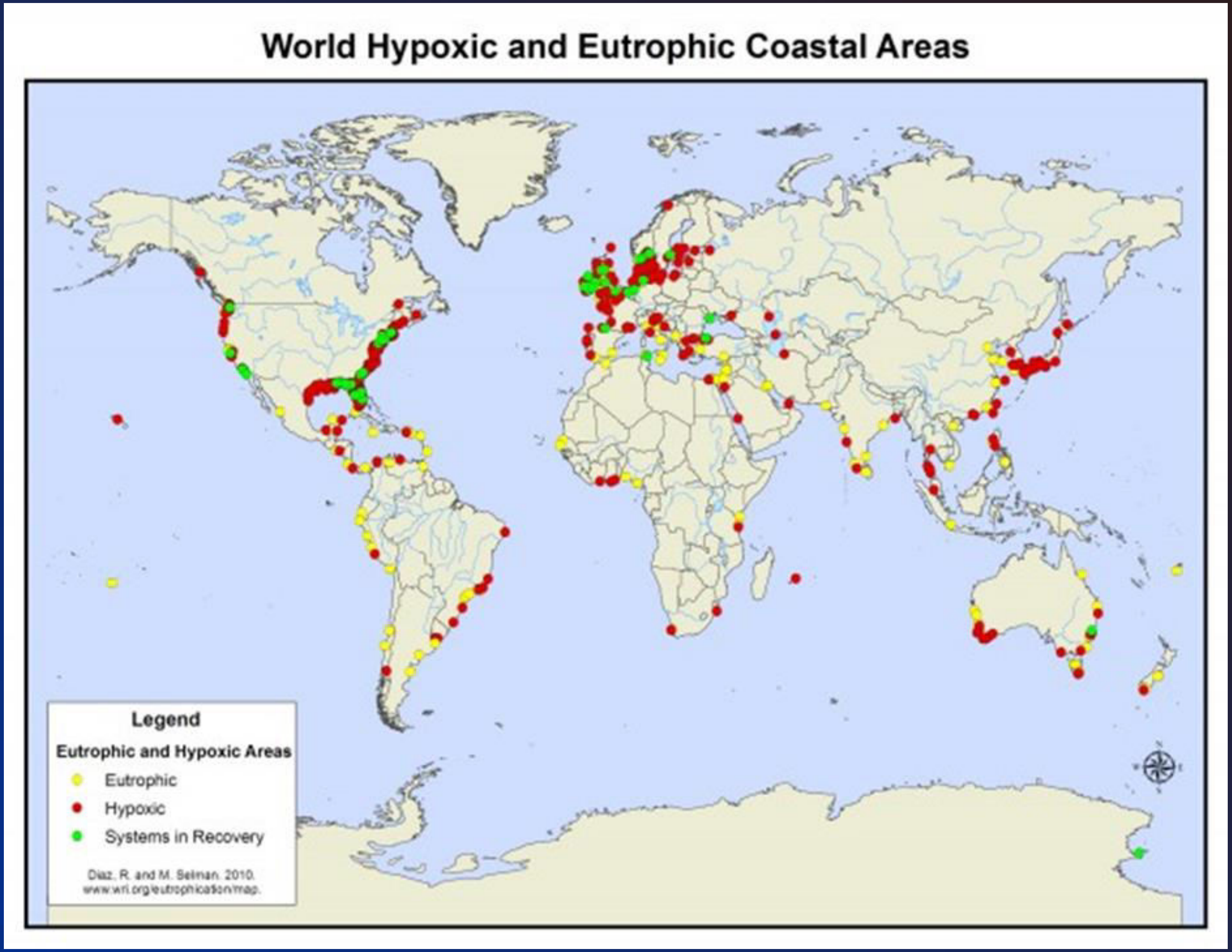
Common definitions (Steckbauer, et al, 2011):

oxygen levels < 2mg/L
organisms exhibit stress

oxygen levels < 0.5 mg/L
mass mortality

Normal levels > 3 mg/L

Hypoxia and eutrophication globally

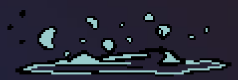


From World Resources Institute at http://www.wri.org/map/world-hypoxic-and-eutrophic-coastal-areas

Affect on Ecosystem Services

Micro (species) level

- death,
- reduced reproductive success,
- interruptions of food webs,
- lost habitat,
- increased predation



Macro level (fish stock, catch etc.)

- Some examples of major effects, but overall not a lot…
- Mobile species exit zone, move outside,
- "A number of compensatory mechanisms limit the translation of local scale effects of hypoxia to the scale of the whole system" Breitburg, et al. Annual Review of Marine Science, 2009
- Concerns: long run effects, hysteresis effects, different equilibrium ecosystem
- Much remains unknown

Case Study: The Black Sea

http://www.iapscience.com/img/Black_Sea_map.png Institute for Applied Science

The Black Sea

Most of the agricultural run-off enters from the Danube River

Sediment clouds the Sea of Azov (NASA's Aqua satellite; May 2004)

Phytoplankton blooms and plumes of sediment form the bright blue swirls that ring the Black Sea

http://visibleearth.nasa.gov/images/6426/BlackSea.A2004143.1105.250m.jpg

Chronology of the Black Sea Events Related to Hypoxic Zone

1960s: large increase in agricultural nutrients, industrial and human waste contributions

1973: 2500 km^2 summer hypoxia

1978: 30,000 km^2

1989: 40,000 km^2 , mass mortality of benthic organisms

Simultaneous problems: overfishing, introduction of invasive species (jellyfish)

1980 on: major losses in fish stock and fishery output, estimates of $2 billion lost revenue, $500 million lost tourism expenditures, >20,000 serious waterborne illnesses, host of other issues not quantified

Chronology of the Black Sea Events (continued)

Meanwhile….

1980s on: collapse of economic system ala Soviet Union collapse lead to rapid reductions in fertilizer usage and animal agriculture,

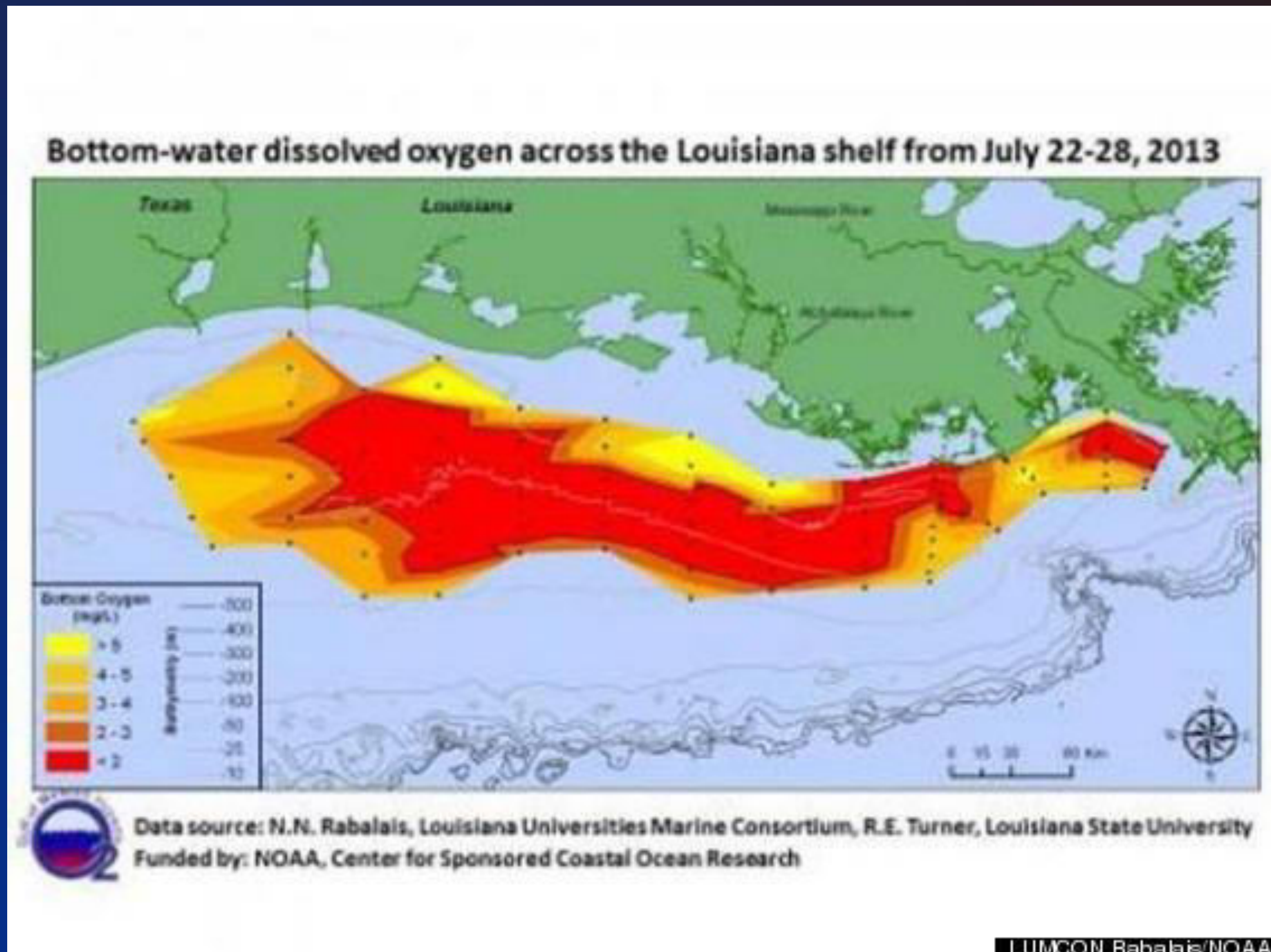
1990s: within 6 years, major improvement in benthic populations

Today: new economic growth and development, problems re-emerging

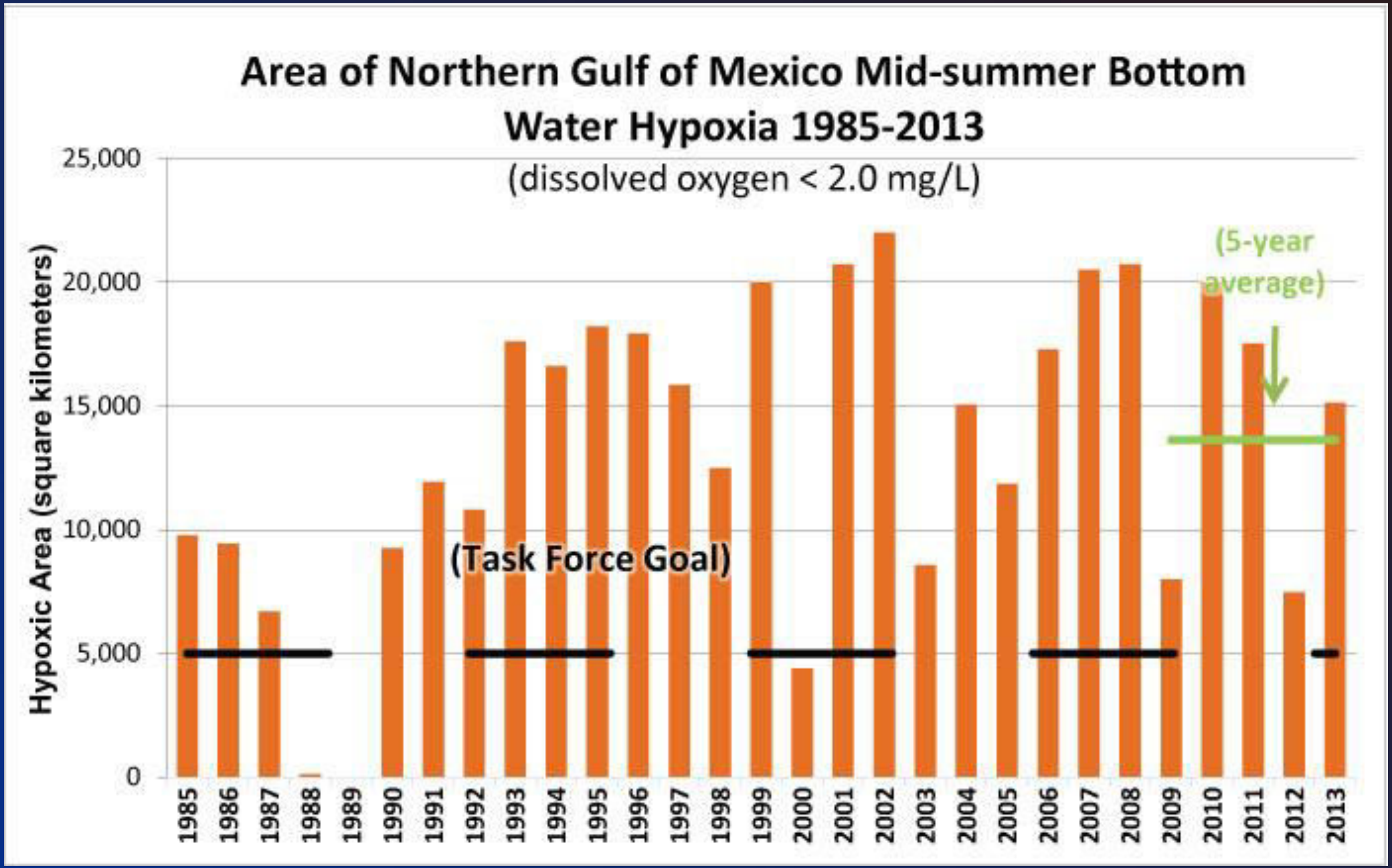
Gulf of Mexico Dead Zone and Watershed, MARB

http://www.umces.edu/people/boesch-gulf-mexico-hypoxia

Northern Gulf of Mexico Dead Zone, 2013



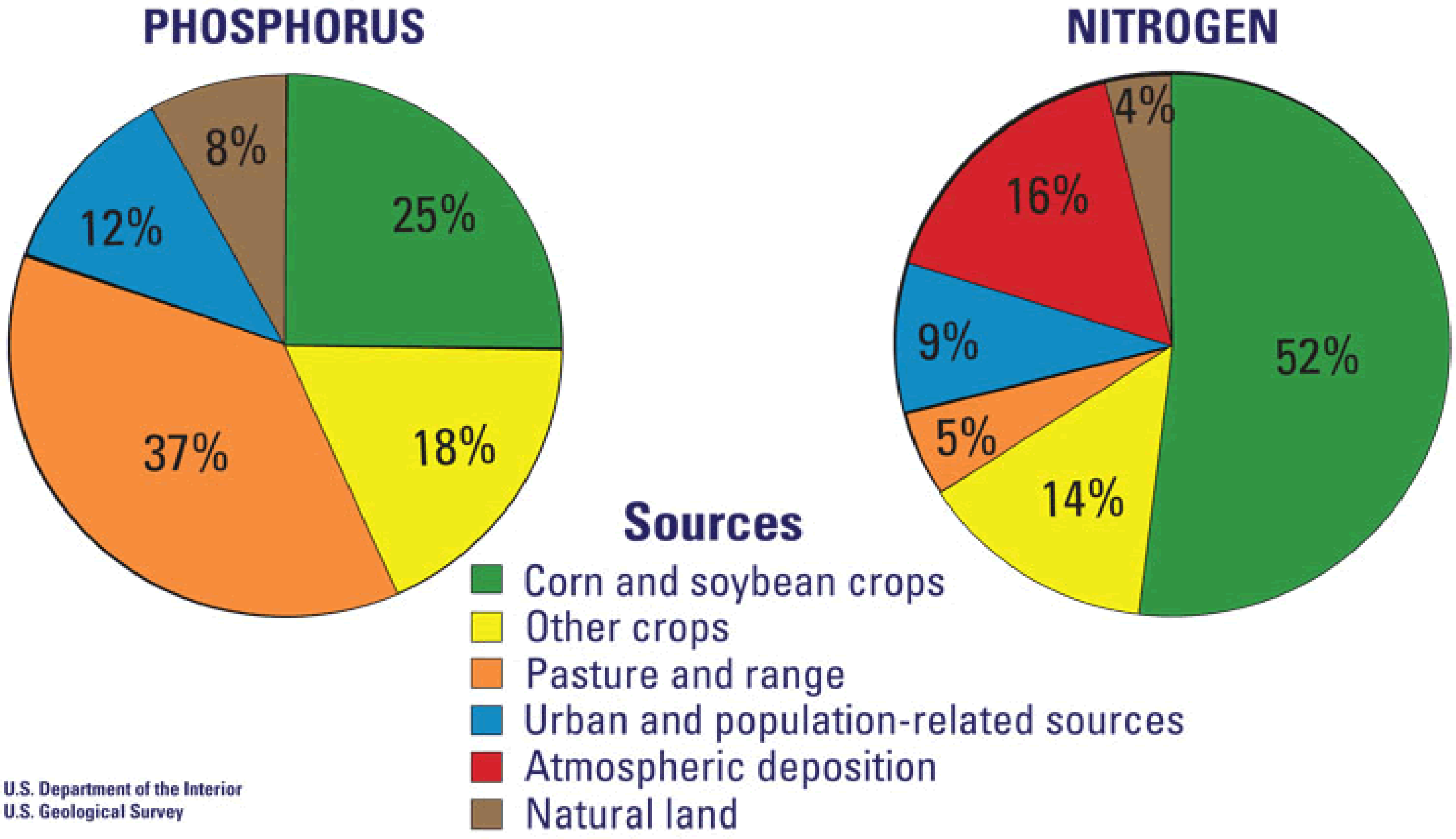
Northern Gulf of Mexico Hypoxia



http://water.epa.gov/type/watersheds/named/msbasin/index.cfm

USGS
science for a changing world

Sources of nutrients delivered to the Gulf of Mexico



U.S. Department of the Interior
U.S. Geological Survey

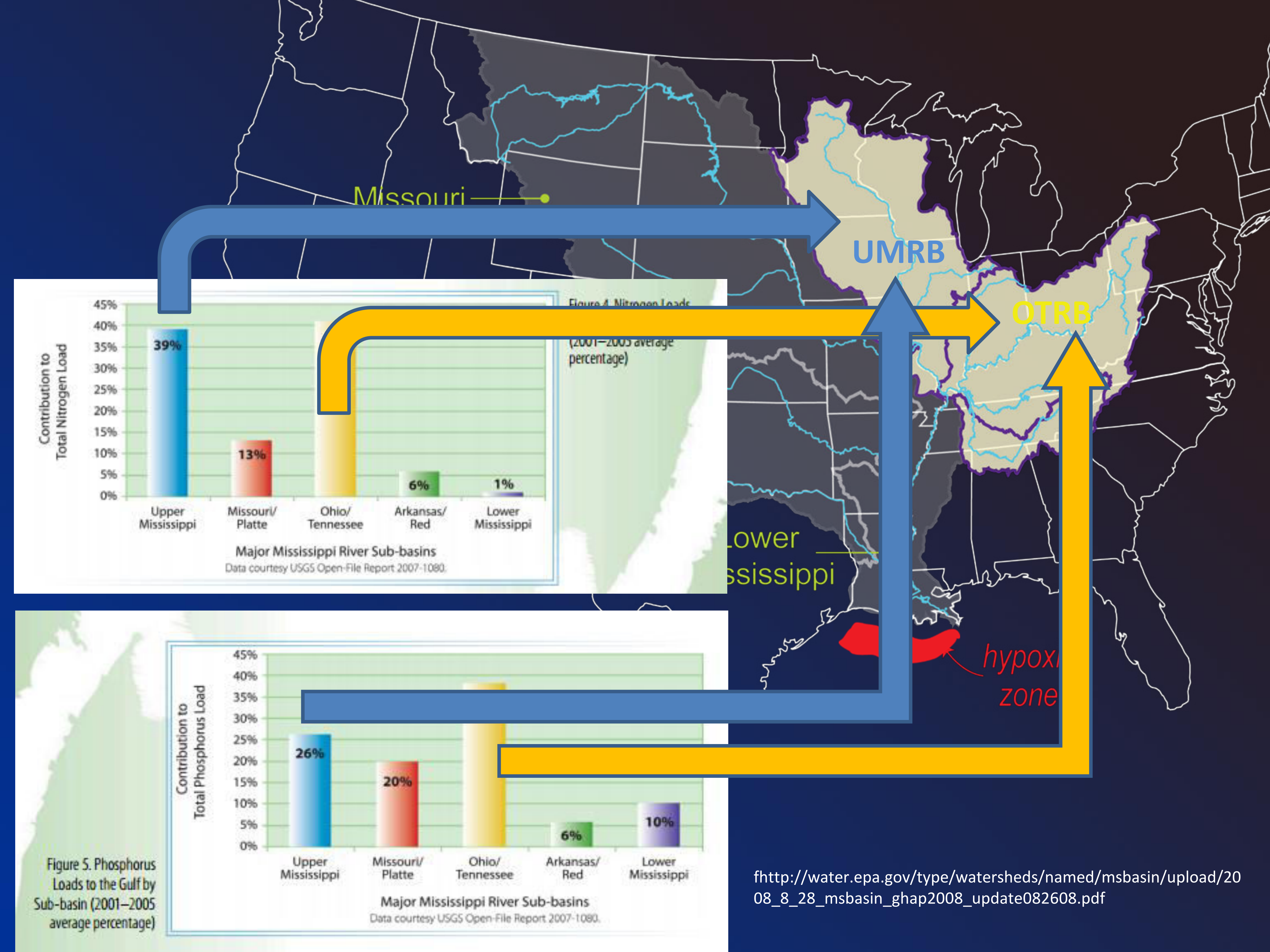


Figure 5. Phosphorus Loads to the Gulf by Sub-basin (2001–2005 average percentage)

fhttp://water.epa.gov/type/watersheds/named/msbasin/upload/2008_8_28_msbasin_ghap2008_update082608.pdf

Approaches to Reduce Nutrient Runoff

- Phosphorus
  - Reduced (no) tillage
  - Buffers
  - Grassed Waterways
- Nitrogen
  - Manure and fertilizer management
  - Denitrification, controlled drainage
- Both
  - Cover crops, rotation changes
  - Wetlands
  - Land retirement

Buffers and Terracing

Land Retirement

Panoramic view of gamma grass-big blue stem planting
http://www.fsa.usda.gov/Internet/FSA_Image/ia_767_15.jpg

Where should we target conservation efforts across this broad expanse to most cost effectively achieve reductions in the hypoxic zone size?

1. Effectiveness of these practices in reducing N and P loading vary depending on
   - The soils
   - The cropping patterns and history
   - Location in the watershed
   - Other land uses in the watershed

2. Costs of the practices vary
   - Some are low cost: e.g., reduced tillage increases profits in some locations
   - Some are high cost – taking land out of production is very expensive

3. For cost effectiveness want to target by both costs and benefit

Three key components of modeling strategy:

1. Landscape scale watershed-based model of agricultural land use
   - Cover the entire MARB
   - Simulate how changes in agricultural practices change nutrient runoff at each location
   - Simulate how all of those interact
   - Simulate the movement of nutrients throughout the MARB and delivered to the Gulf
   - Costs of those practices

   National CEAP Assessments: Major NRCS/USDA effort

2. Model of hypoxic zone size

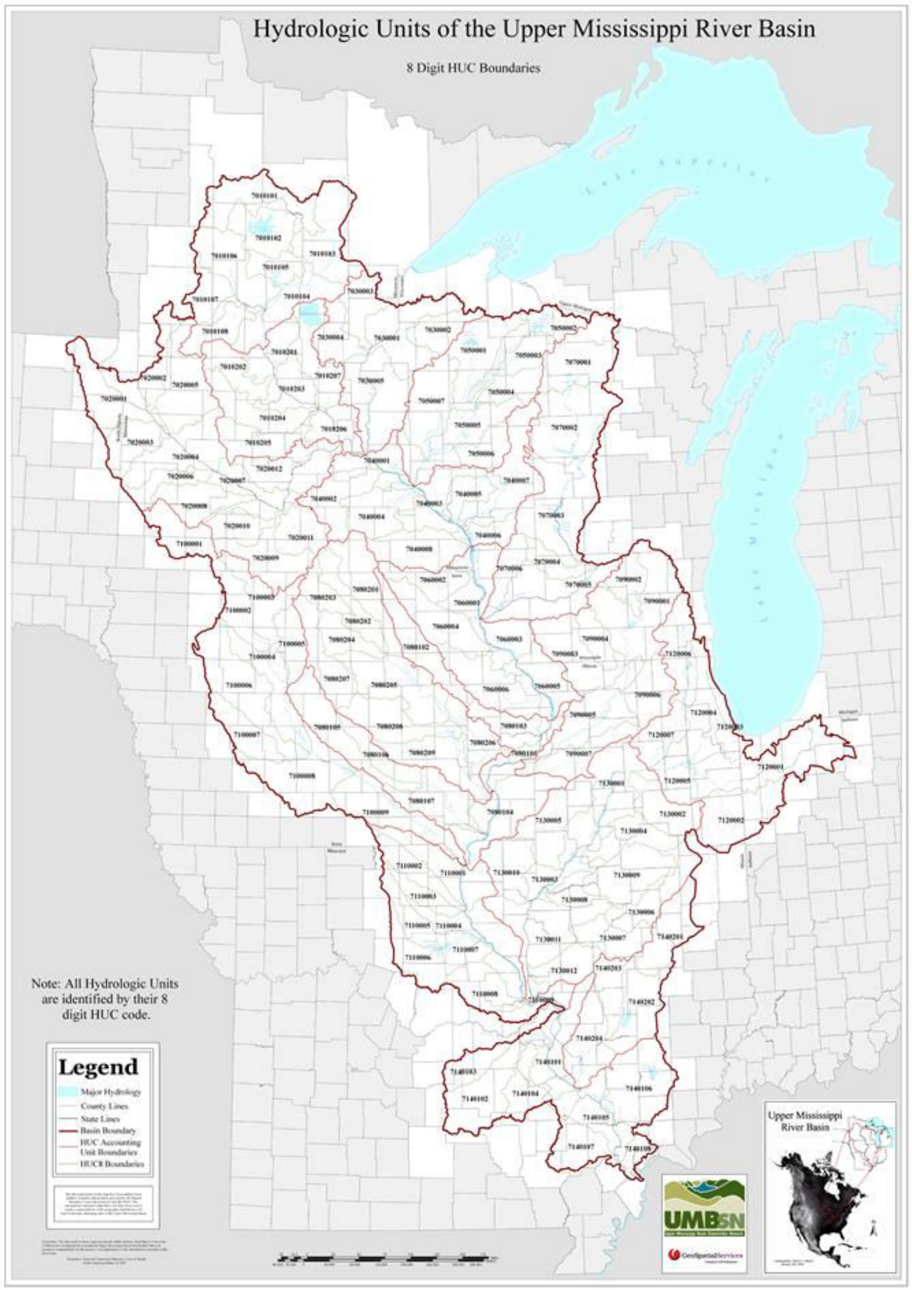
   Rabotyagov new model estimates

3. Procedure to find least cost combination of watersheds to apply conservation practices

   Evolutionary Algorithm (SPEA)

USDA-NRCS Conservation Effects Assessment Project

- Landscape scale watershed-based model of agricultural land use
- Multi year effort, goal to evaluate effectiveness of USDA conservation programs
- Quantified the effects of existing conservation practices on water quality
- Developed models, detailed land use representations, data rich
- Developed scenarios for cost and effectiveness of increased conservation practices



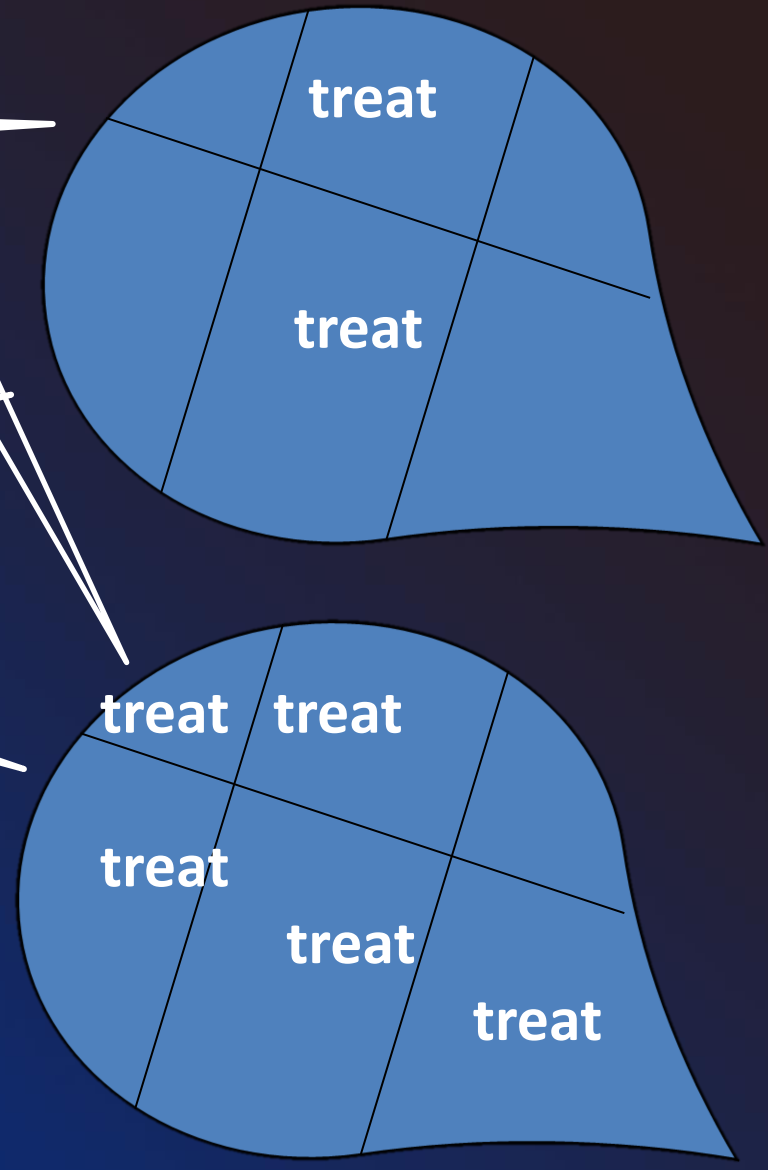
1. CEAP- UMRB Watershed Model (USDA,NRCS Team)

- Used 3 years of detailed farm management data, NRI, soil survey, conservation plan records, 47 years of weather to populate model
- 131 sub-basins in UMRB
- Integrated SWAT and APEX models to evaluate the effects of existing conservation practices
- Also developed scenarios of increased conservation practice application

CEAP Scenarios

HUC 8: 70001111

- Erosion Control: Critical or All needed acreage
  - terraces on high slopes, contour or strip cropping on all, buffers near waterways, filter strips elsewhere
- Nutrient Management: Critical or All Acreage
  - erosion control + adjusted rate, form, timing, and method of application to be most efficient
- BACK
  - retire agricultural land



2. New empirical hypoxic zone model

Hypoxia zone size = f(nutrient loads, currents, hurricanes)

- Rabotyagov: model allows lagged nutrient inputs without using up many degrees of freedom (Polynomial distributed lag model)
- USGS data estimates, LUMCON data on size of zone
- Existing models: Turner et al., 2006; Greene et al., 2009; Forrest et al., 2012; Feng et al., 2012

Both nitrogen and phosphorus

Legacy and stock effects

ntrol for turbance events - currents and hurricanes

Rabotyagov PDL Model

$$Hypoxic\ Zone_t = \beta_{intercept} + \beta_{hurricane} Hurricane_t +$$

$$\beta_{current} Current_t + \beta_{hurrSN} Hurricane_t * log10(Nstock5_t)$$

$$+\beta_{hurrSP} Hurricane_t * log10(Pstock5_t) + \beta_N P_t$$

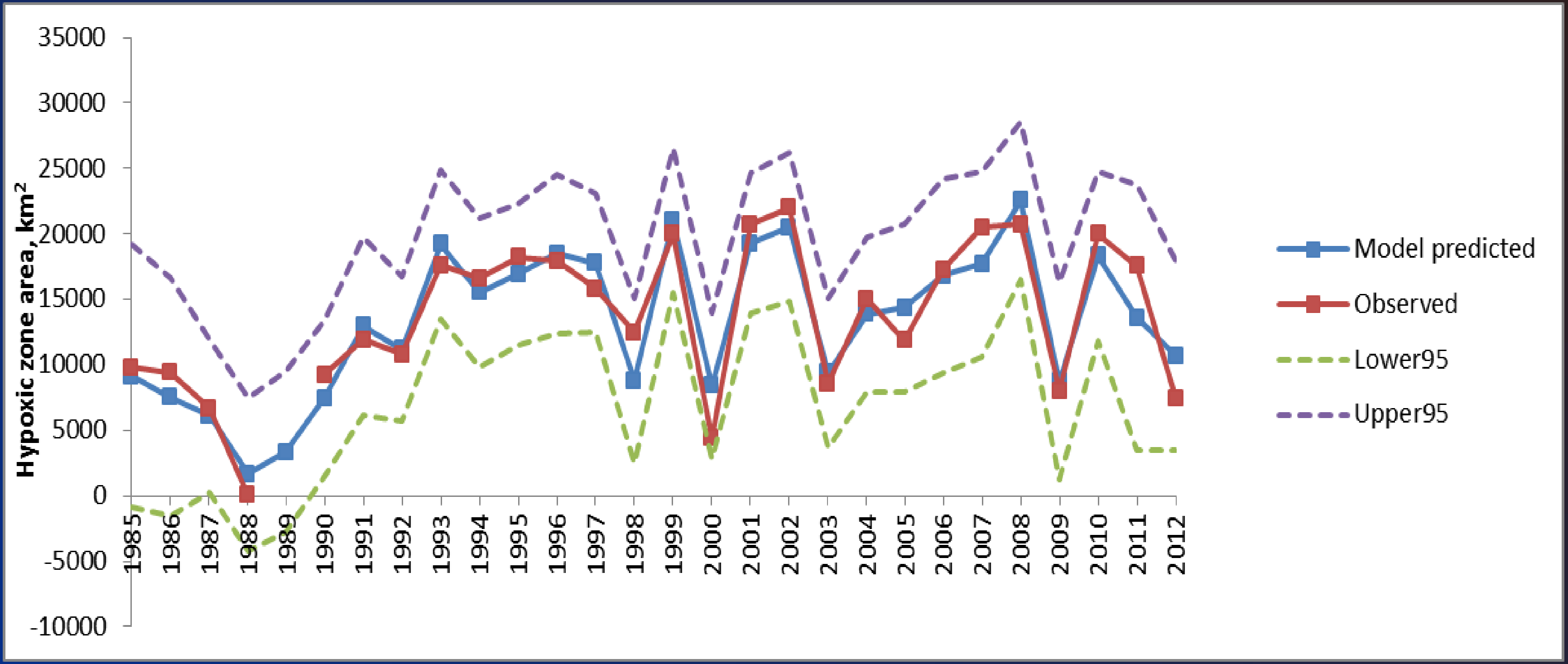
$$+ \sum_{i=0}^{5} \beta_{i,N} N_{t-i} + \beta_{Nstock5} Nstock5_t + \beta_{Pstock5} Pstock5_t + \varepsilon_t$$

Model Estimates

Parameter Estimates				
Variable Description	Estimate	Standard Error	t Value	p-value
Intercept	-670443	170396	-3.93	0.0017
Hurricane	164110	183151	0.90	0.3865
Currents	-13637	2776	-4.91	0.0003
log10N**0	55315	16013	3.45	0.0043
log10N**1	-18924	5398	-3.51	0.0039
Log10(current year t May N)	33892	9630	3.52	0.0038
Log10(year t-1 May N)	29368	8381	3.50	0.0039
Log10(year t-2 May N)	24844	7146	3.48	0.0041
Log10(year t-3 May N)	20321	5936	3.42	0.0045
Log10(year t-4 May N)	15797	4767	3.31	0.0056
Log10(year t-5 May N)	11273	3681	3.06	0.0091
log10P, year t TP	6803	4961	1.37	0.1935
Nstock5	-0.0827	0.0336	-2.46	0.0285
Pstock5	0.4424	0.0854	5.18	0.0002
hurrStockN5	283848	187917	1.51	0.1548
hurrStockP5	-371761	192792	-1.93	0.0759
AR1 (theta1)	0.4043	0.1628	2.48	0.0274
AR2 (theta2)	0.8117	0.1511	5.37	0.0001

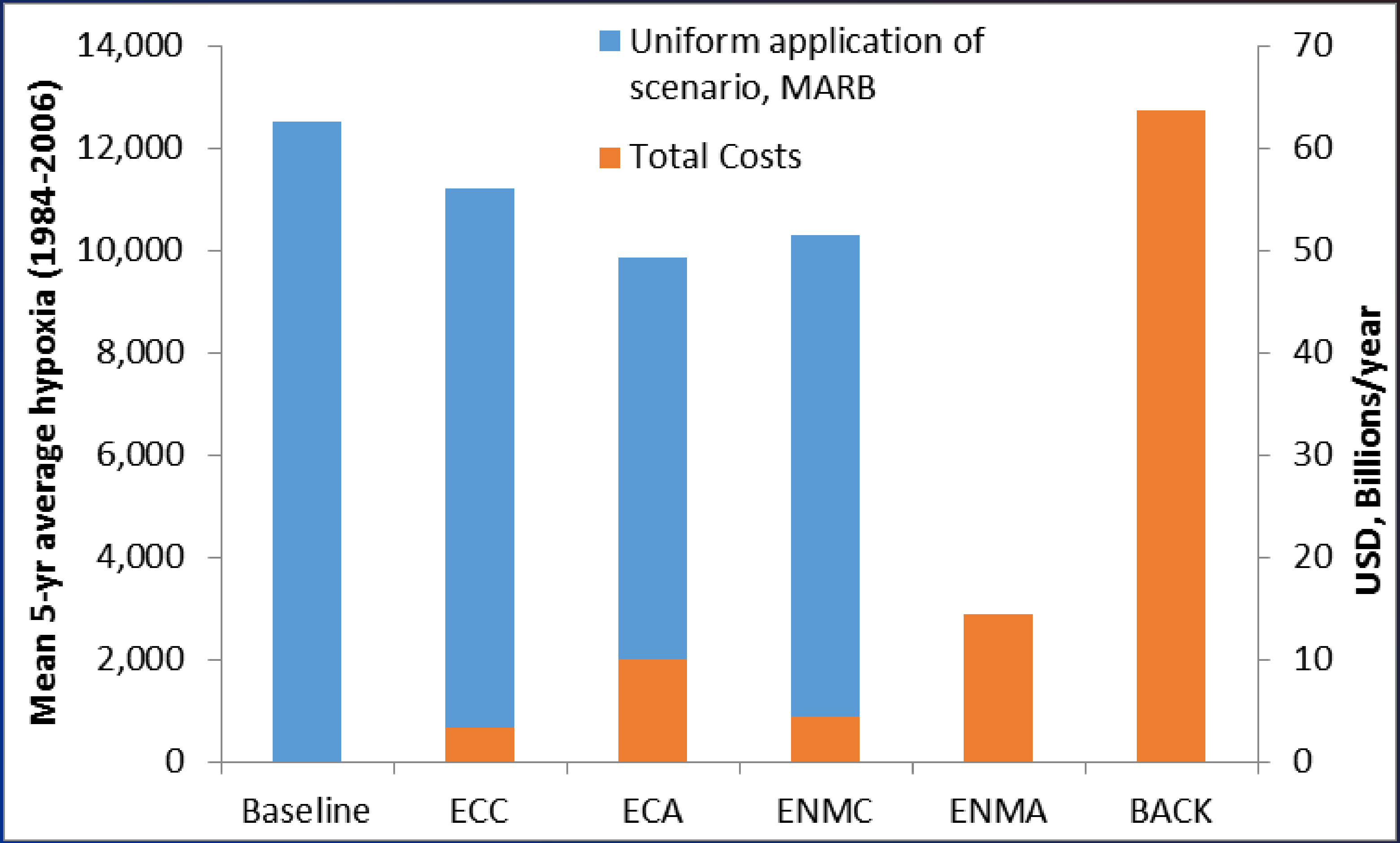
AIC	470.746168
AICC	496.746168
HQC	474.80294
Regress R-Square	0.9503
Total R-Square	0.9085
Observations	25

Model performance

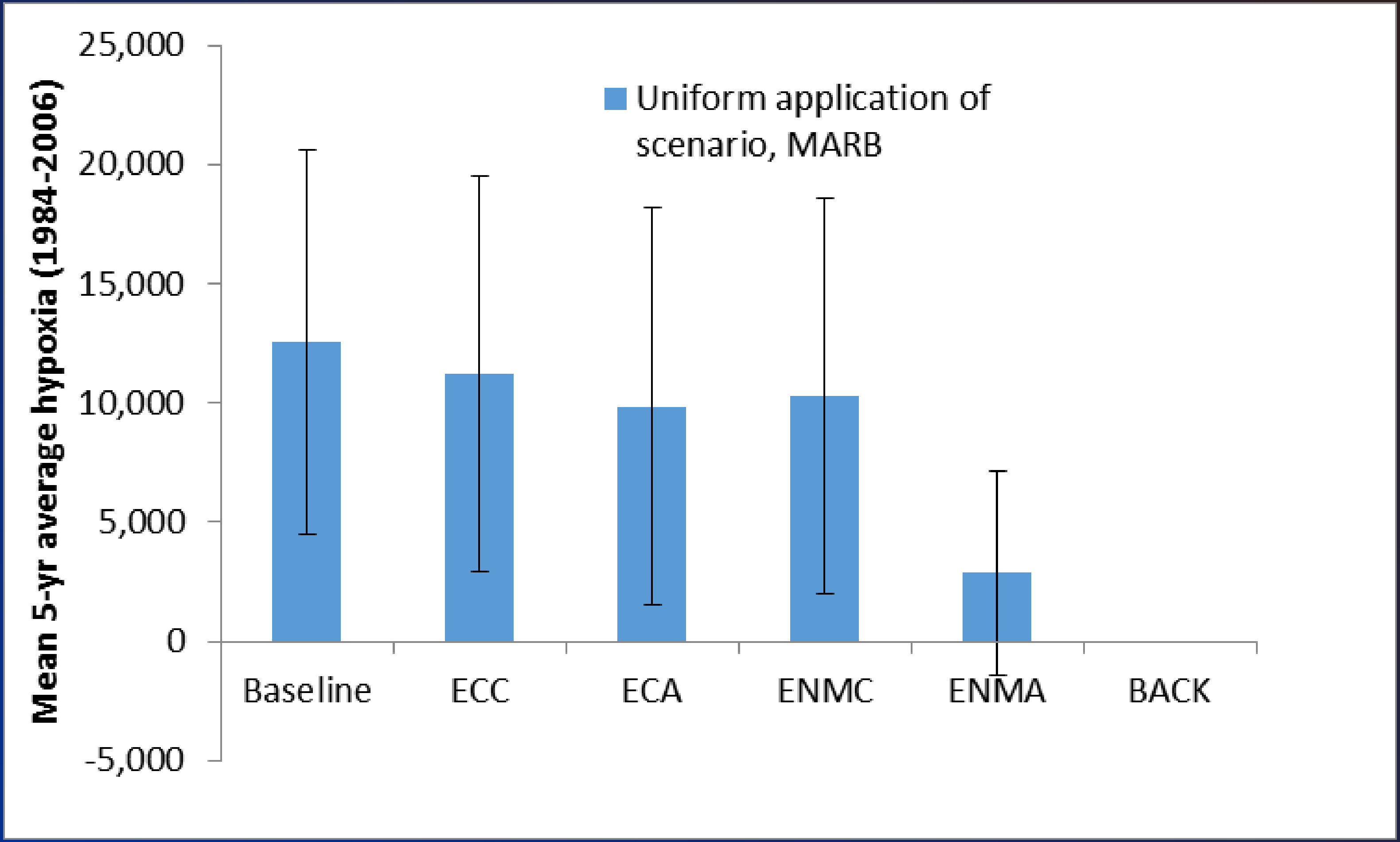


- Regression R^2=0.95 (we are mostly interested in the structural part, as opposed to prediction)
- Leave 2011 and 2012 observations out of estimation and see how well the model does in terms of prediction

Initial Results: ENMA across all of MARB reaches goal, cost of $14 billion/year

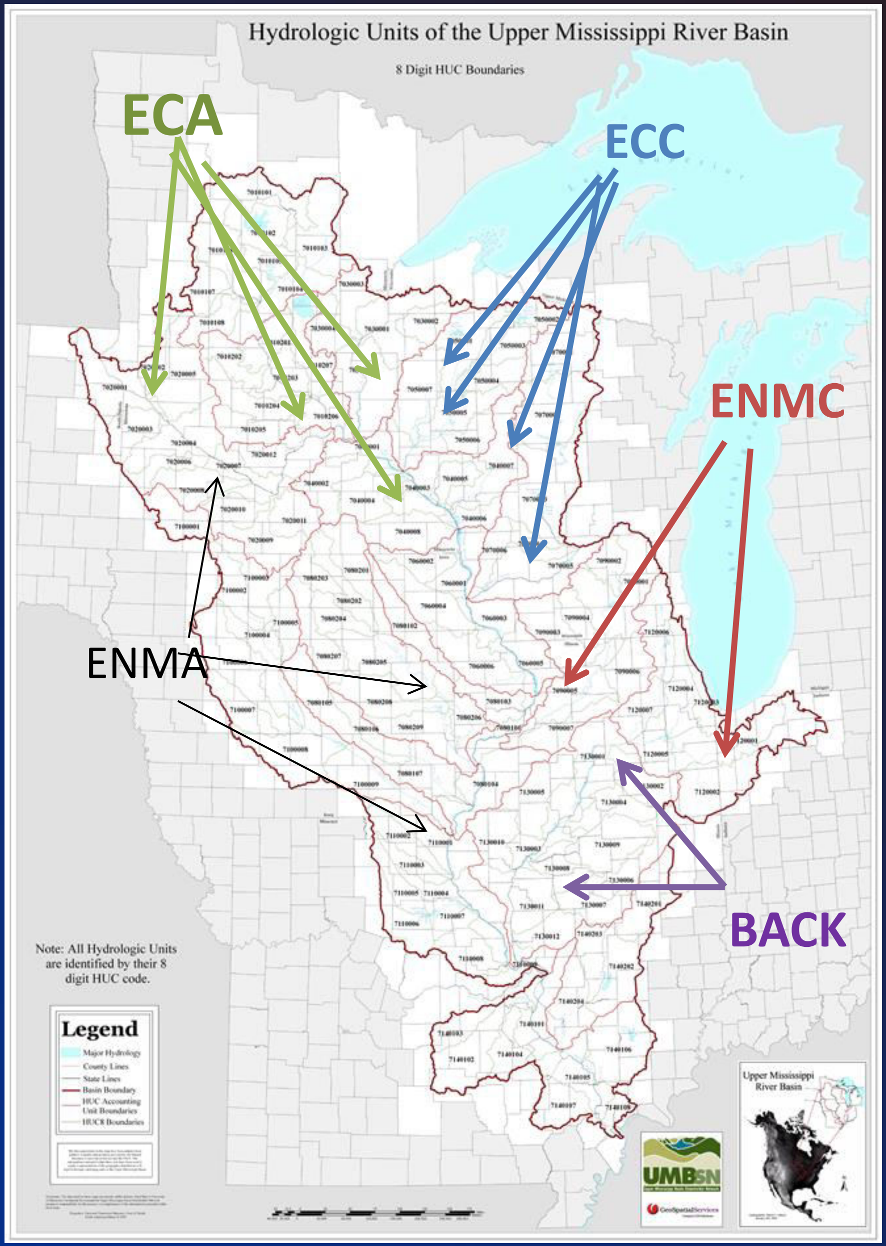


Error Bars are Wide

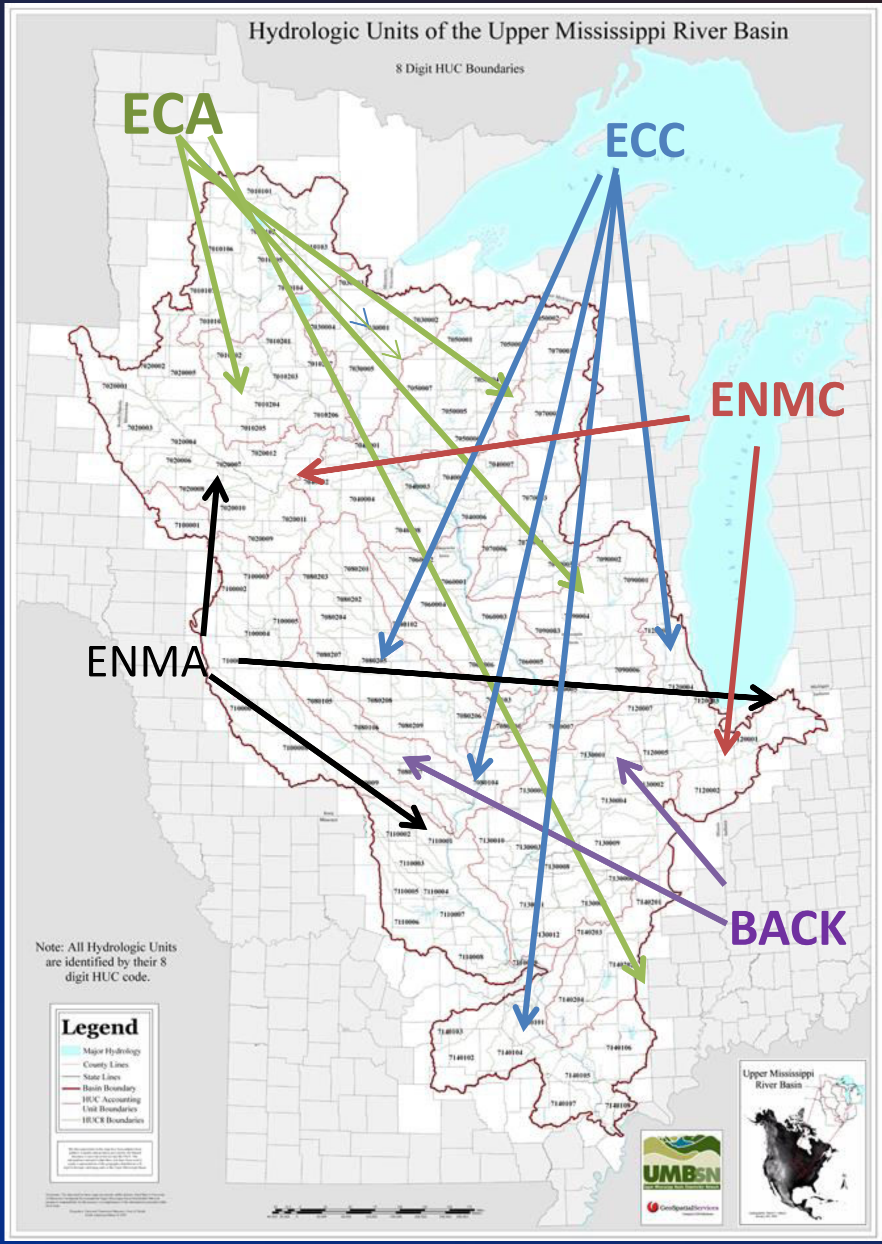


3. Evolutionary Algorithm

- Can we do better by targeting? Instead of treating all 848 sub-watersheds, can we aggressively treat some and achieve cost savings and dead zone reductions?
- Evolutionary algorithms are methods to intelligently search through these options without having to evaluate them all
- Compare the following two watershed configurations


Hydrologic Units of the Upper Mississippi River Basin
8 Digit HUC Boundaries
ECA
ECC
ENMC
ENMA
BACK
Note: All Hydrologic Units are identified by their 8 digit HUC code.
Legend
Upper Mississippi River Basin
UMBSN

OR


Hydrologic Units of the Upper Mississippi River Basin
8 Digit HUC Boundaries
ECA
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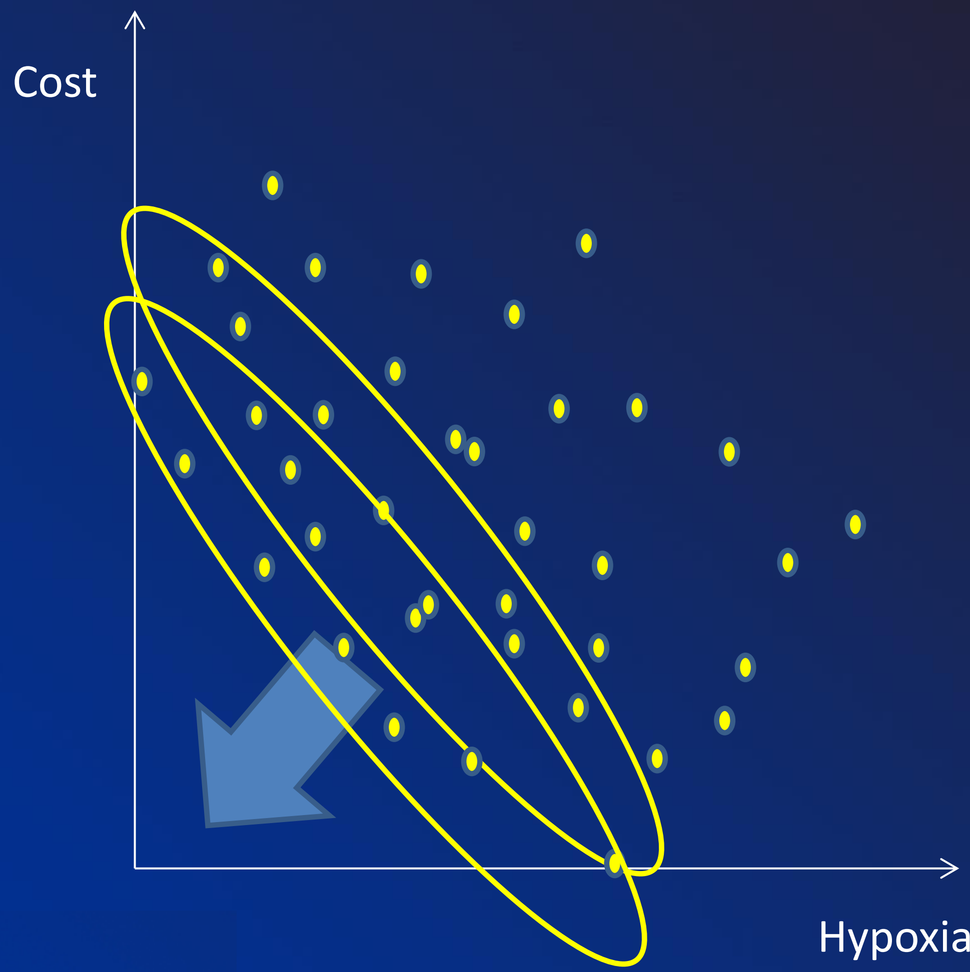
ENMA
BACK
Note: All Hydrologic Units are identified by their 8 digit HUC code.
Legend
Major Hydrology
County Lines
State Lines
Basin Boundary
HUC Accounting Unit Boundaries
HUC8 Boundaries
Upper Mississippi River Basin
UMBSN

Evolutionary Algorithm --intuition



1. Assign each sub watershed one of the six scenarios, evaluate costs and nutrients
2. Do this a bunch of times , create set of yellow dots (each represents a watershed configuration)
3. Keep “best” options (circled) and use those to inform selection of new ones to try
4. Generate new ones and select the best to keep
5. Stop when satisfied, now have a Pareto frontier of options

http://www.jove.com/video/4009/spatial-multiobjective-optimization-agricultural-conservation

Evolutionary Algorithm Applied to CEAP Model

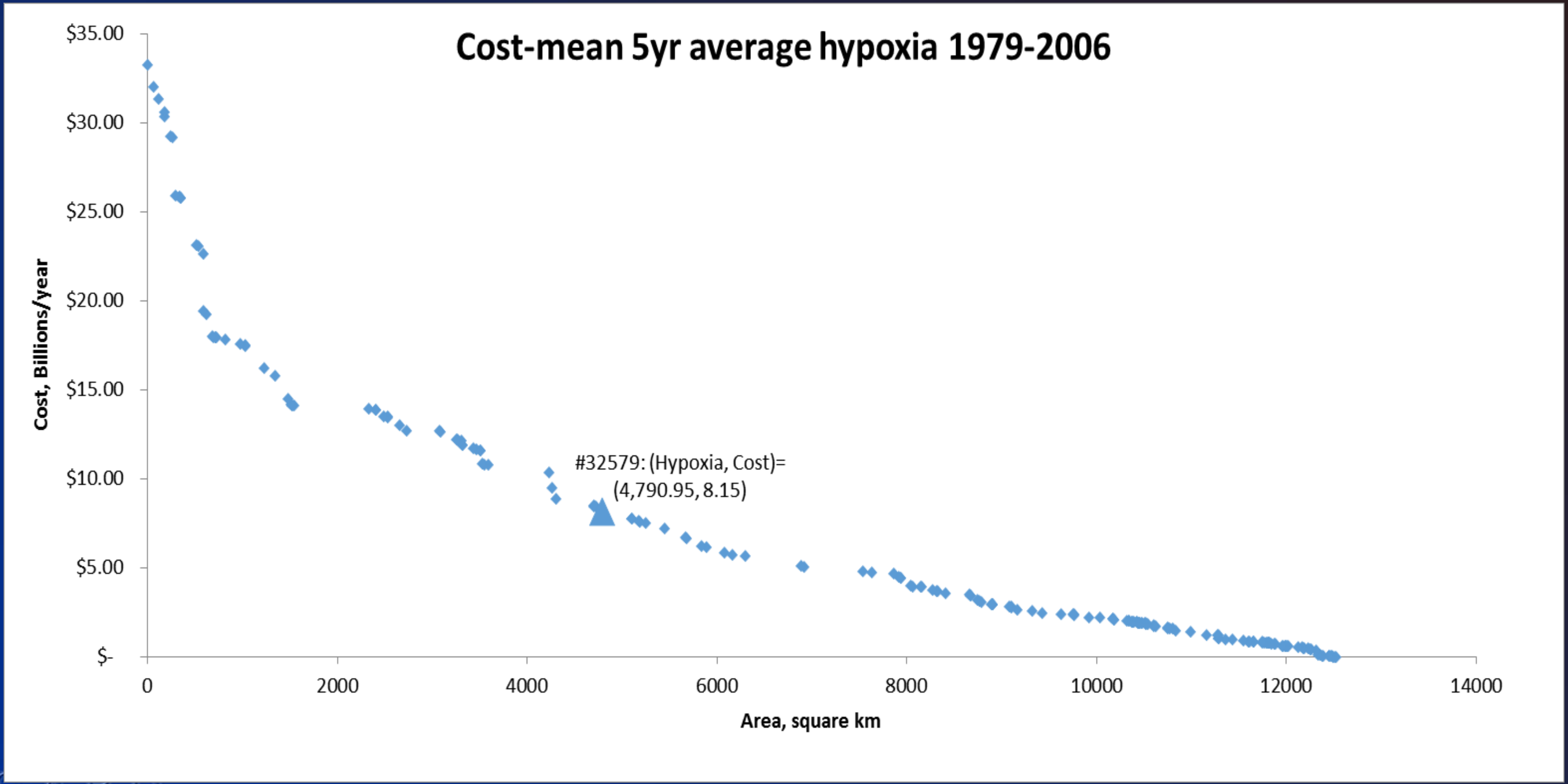
1. 848 subwatersheds in five major basins
2. 6 options for each subwatershed
3. Thus, 6^{848}= GINORMOUS!!
4. Run times significant
5. Optimization run for 5 year average from 2000-2004, re-run frontier for 30 years to create final frontier

More detail than anyone wants to know on run time

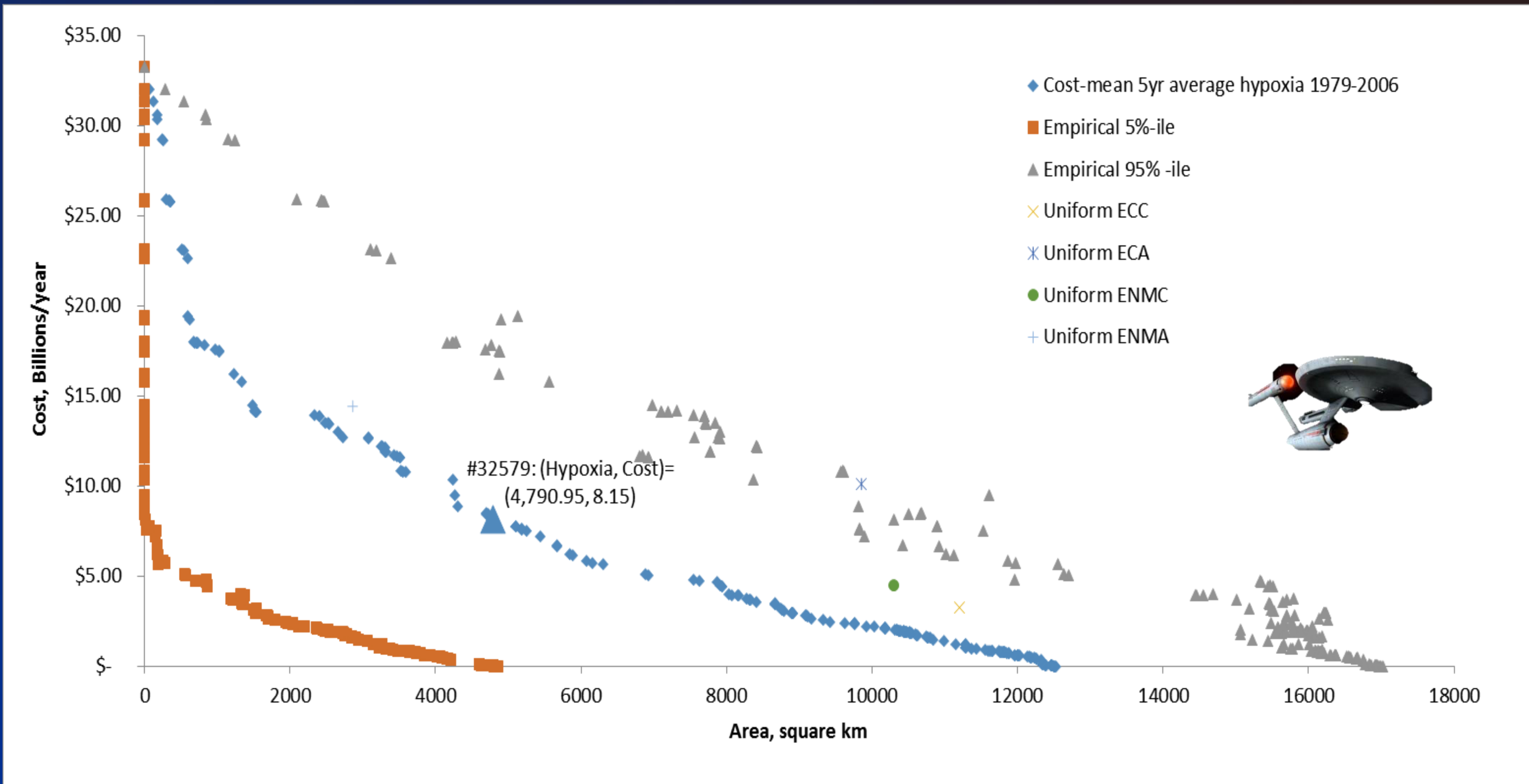
- 1000 generations generated from 12-18-2012 through 03-21-2012 (hours+weekends and break) on a 32-processor Xeon system with 128MB of RAM (20 simultaneous threads).

- After evaluation, completed 859 generations on two machines 08-22 through 09-27-13

Final Frontier

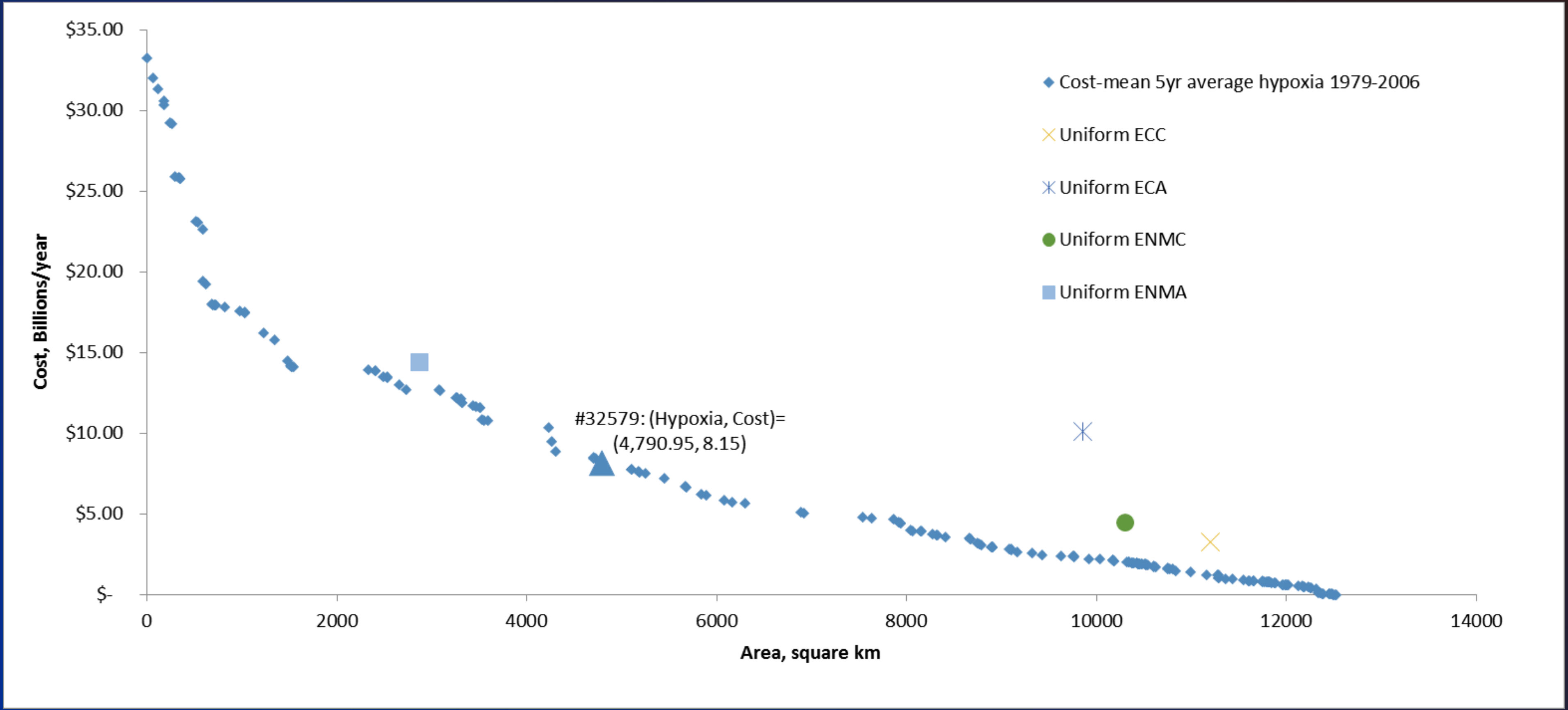


Variability is large



- Empirical 90% CI for 5,000 km2 is (8.7,10300)

Uniform applications are inefficient



- Uniform ENMA over-achieves the goal
- Will likely fare better in terms of local water quality improvements

Solution achieving the Hypoxia goal (4,790 km^2, as mean of 5-year averages)

99.8 million acres treated (roughly even split ENMA & Land Retirement)

16% of all cropland (~8% retired)

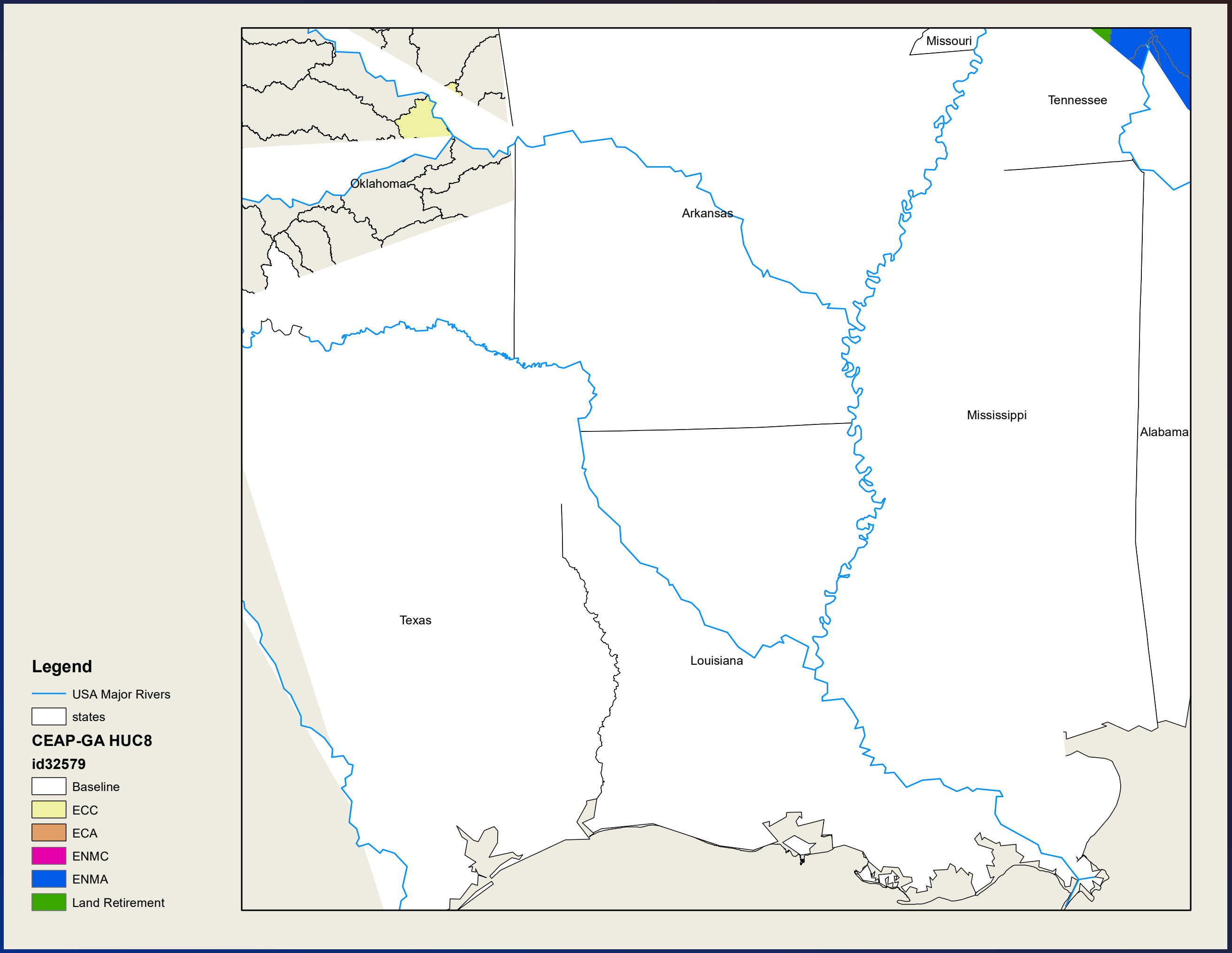
Cost per acre: $81.6

Costs and acreage in the scenario

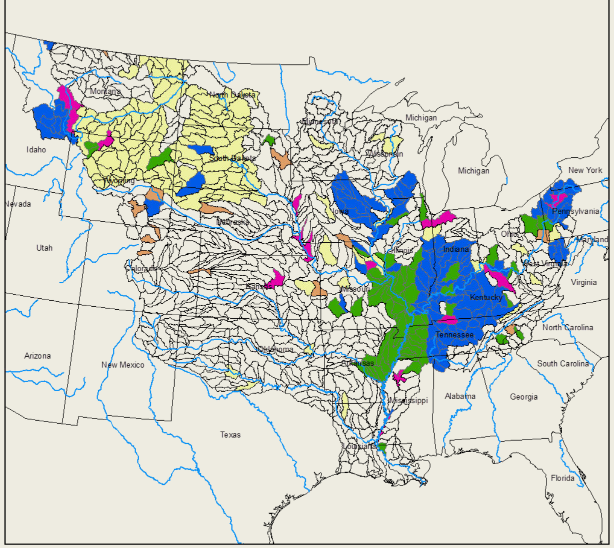
CEAP Scenario	Acreages and Percent of total cropland		Costs and Percent of total cost	
Baseline conservation	520,895,210	83.9%	0	0
ECC	2,832,106	0.5%	$140,120,189	1.7%
ECA	573,138	0.1%	$19,217,578	0.2%
ENMC	1,945,361	0.3%	$103,194,486	1.3%
ENMA	46,596,928	7.5%	$2,884,939,576	35.4%
Land Retirement	47,890,833	7.7%	$4,998,153,444	61.4%

Additional conservation is spatially targeted

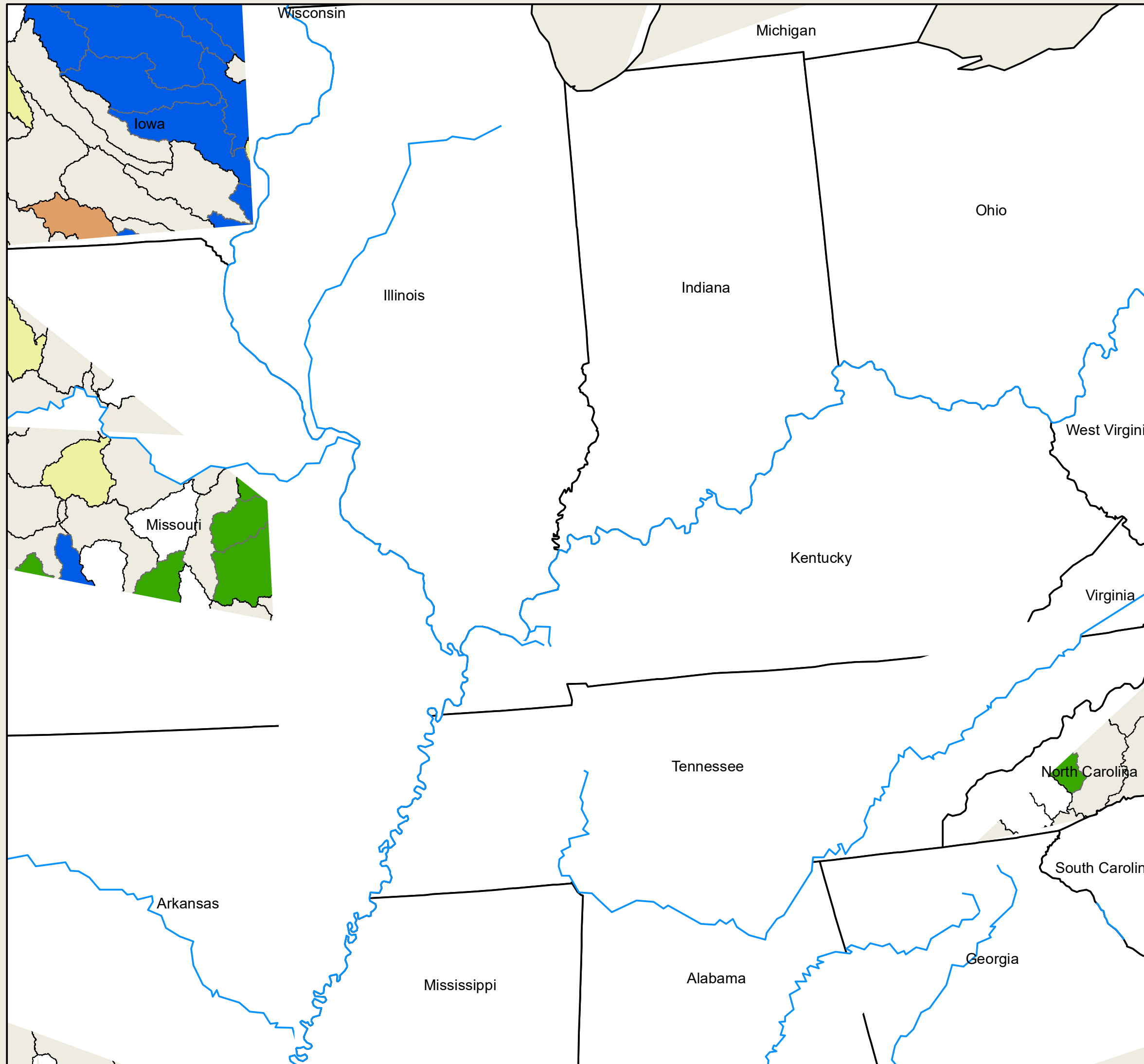
- For example, in the Lower Mississippi, algorithm selects areas around the mainstem



Where is Land Retirement concentrated?

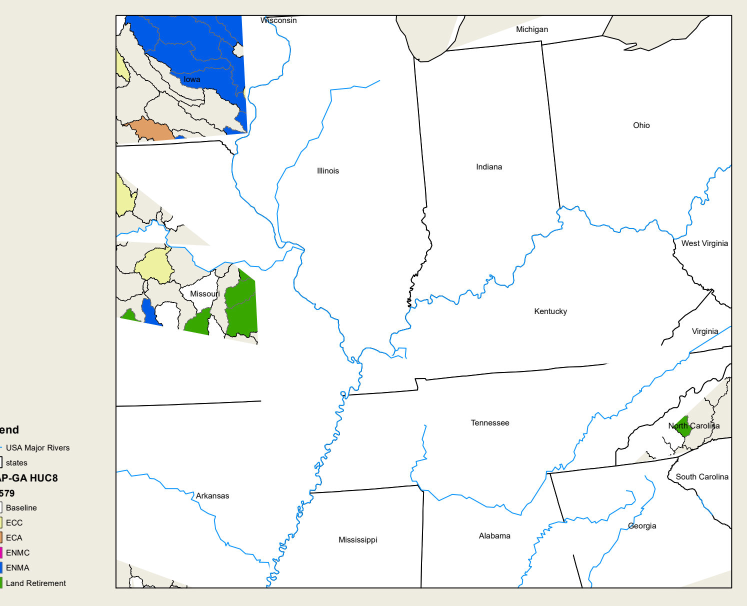


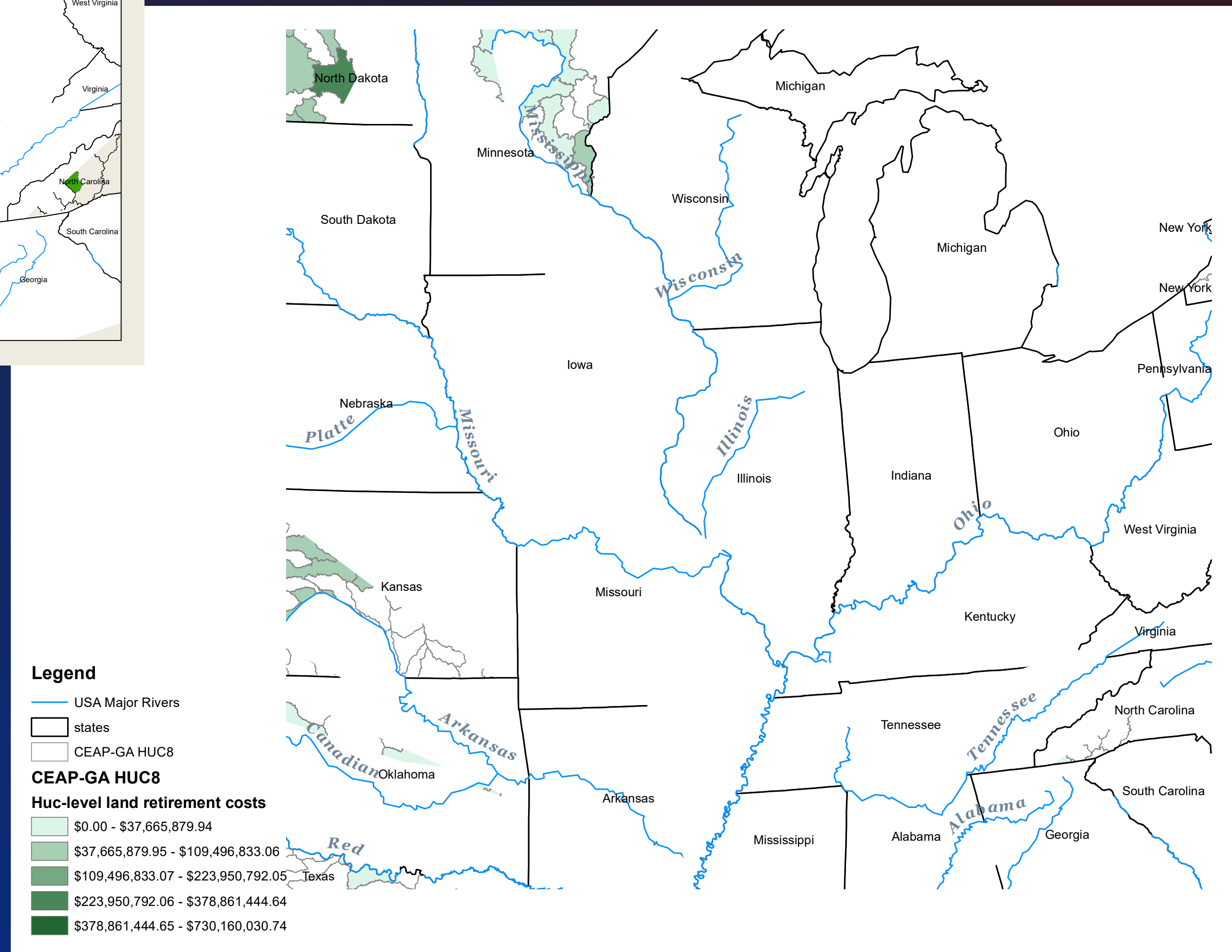
- Arkansas, Tennessee, Missouri, Illinois



Legend

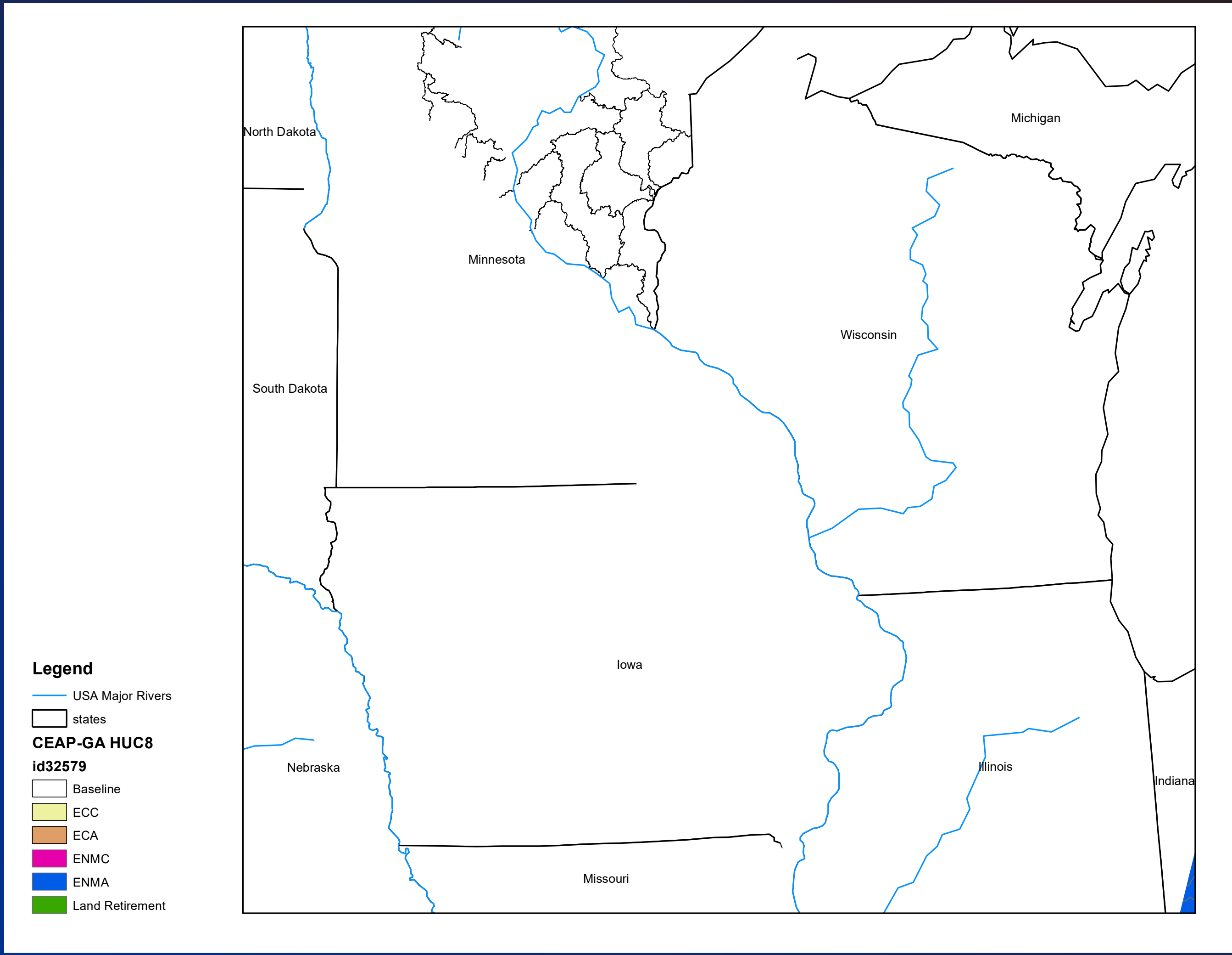
USA Major Rivers
states
CEAP-GA HUC8
id32579
Baseline
ECC
ECA
ENMC
ENMA
Land Retirement





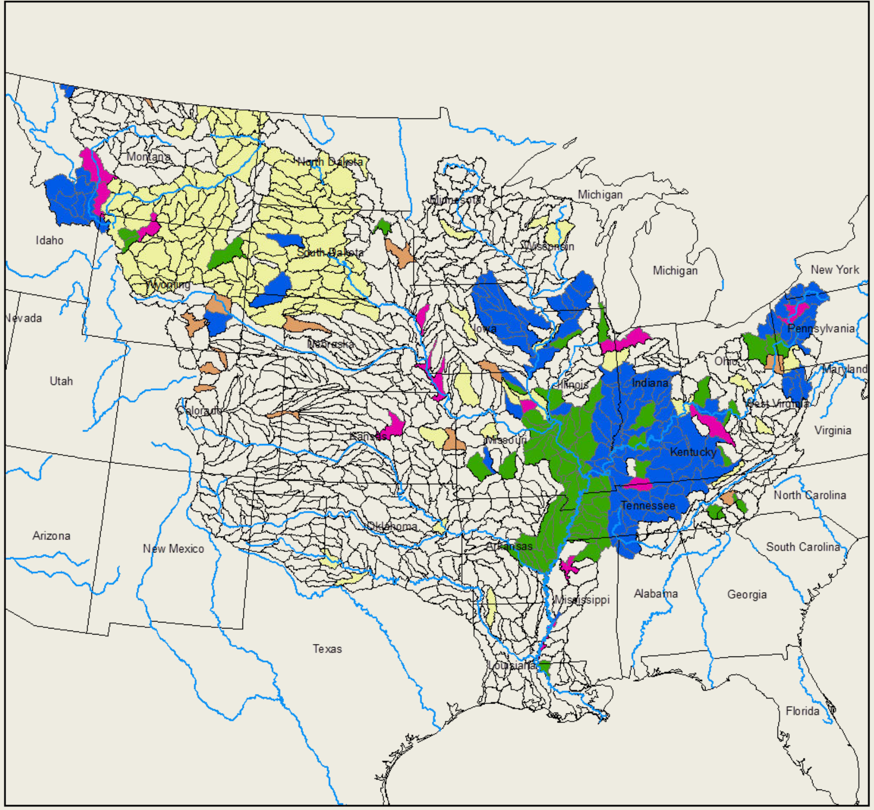
Retiring land in high-cost subwatersheds (in northern Illinois and Iowa) avoided

In Iowa, Minnesota, Wisconsin, N. Illinois: Working land



S. Dakota, N. Dakota, Nebraska, Wyoming and Montana: low cost conservation

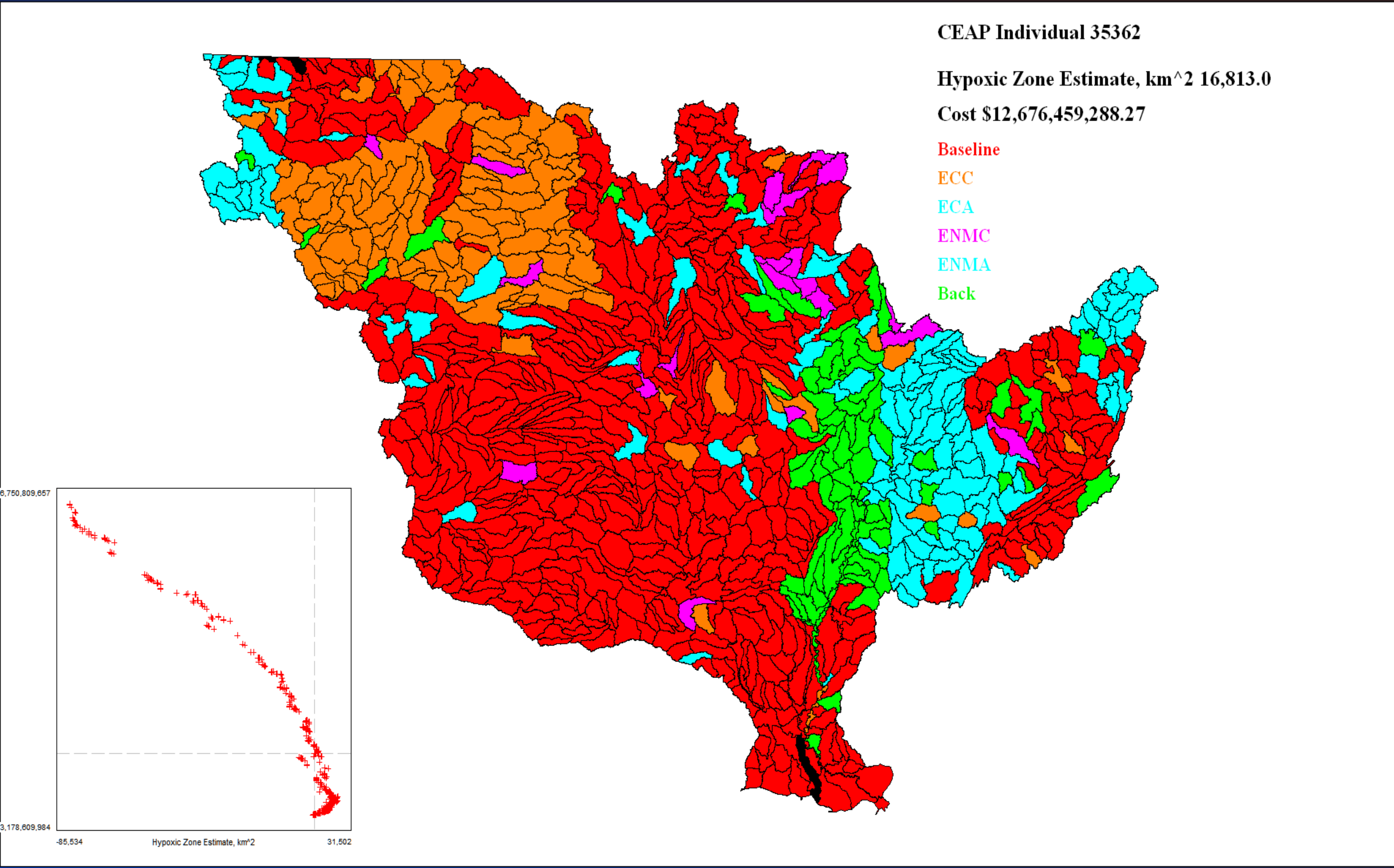
Costs of ENMA scenario



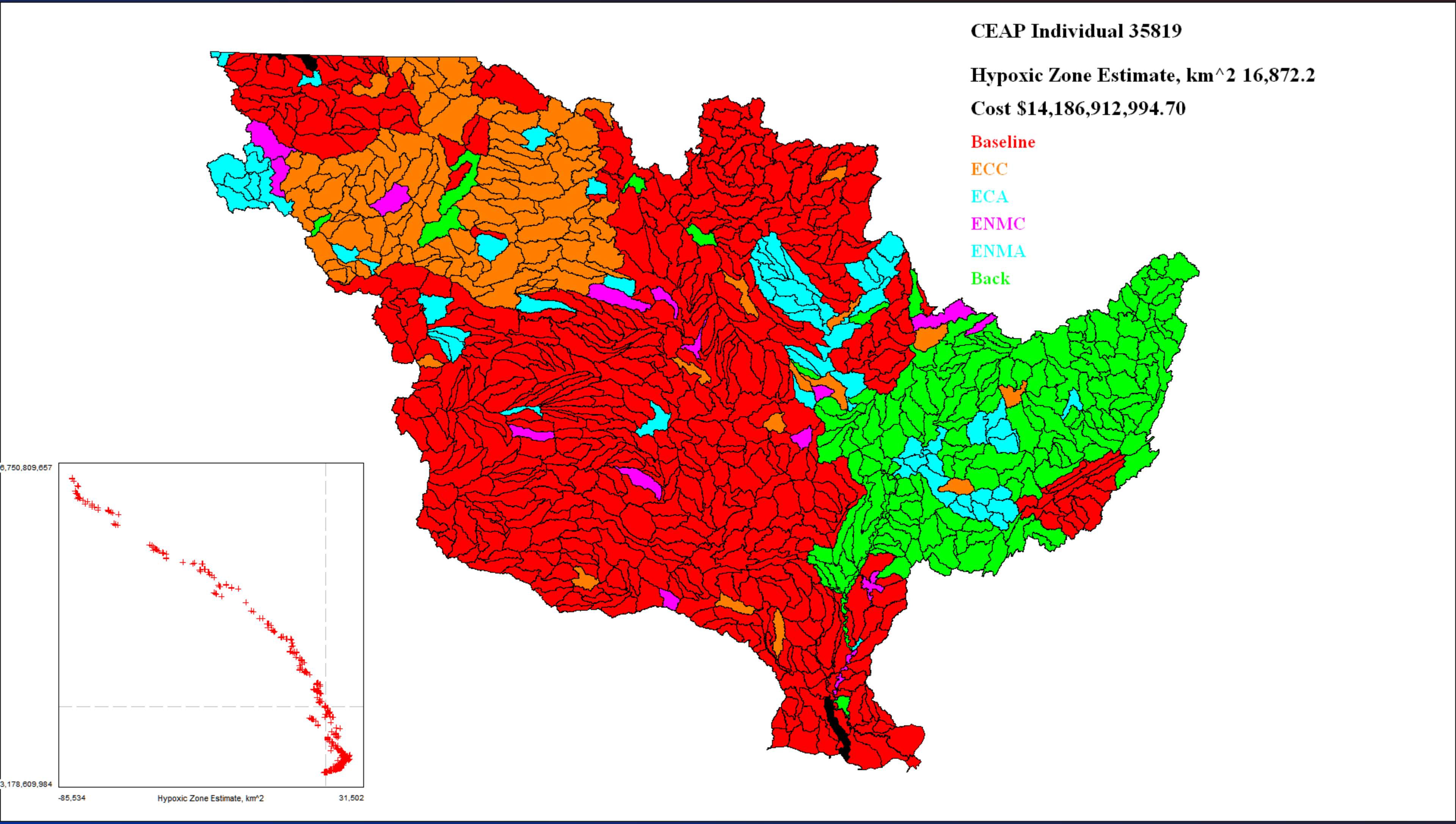
Some high-cost areas selected (effectiveness in reducing nutrients)

Evaluation of unifrom ENMA Scenario

- Can we do better? Yes
  - #35362 achieves similar zone size (2700 km2) at lower cost , $12.7 bn ($1.8 bn savings and lower hypoxia)
  - #35819 cost about the same, $14.2 billion, but achieves average hypoxia of 1500 km2 (about half zone size!)

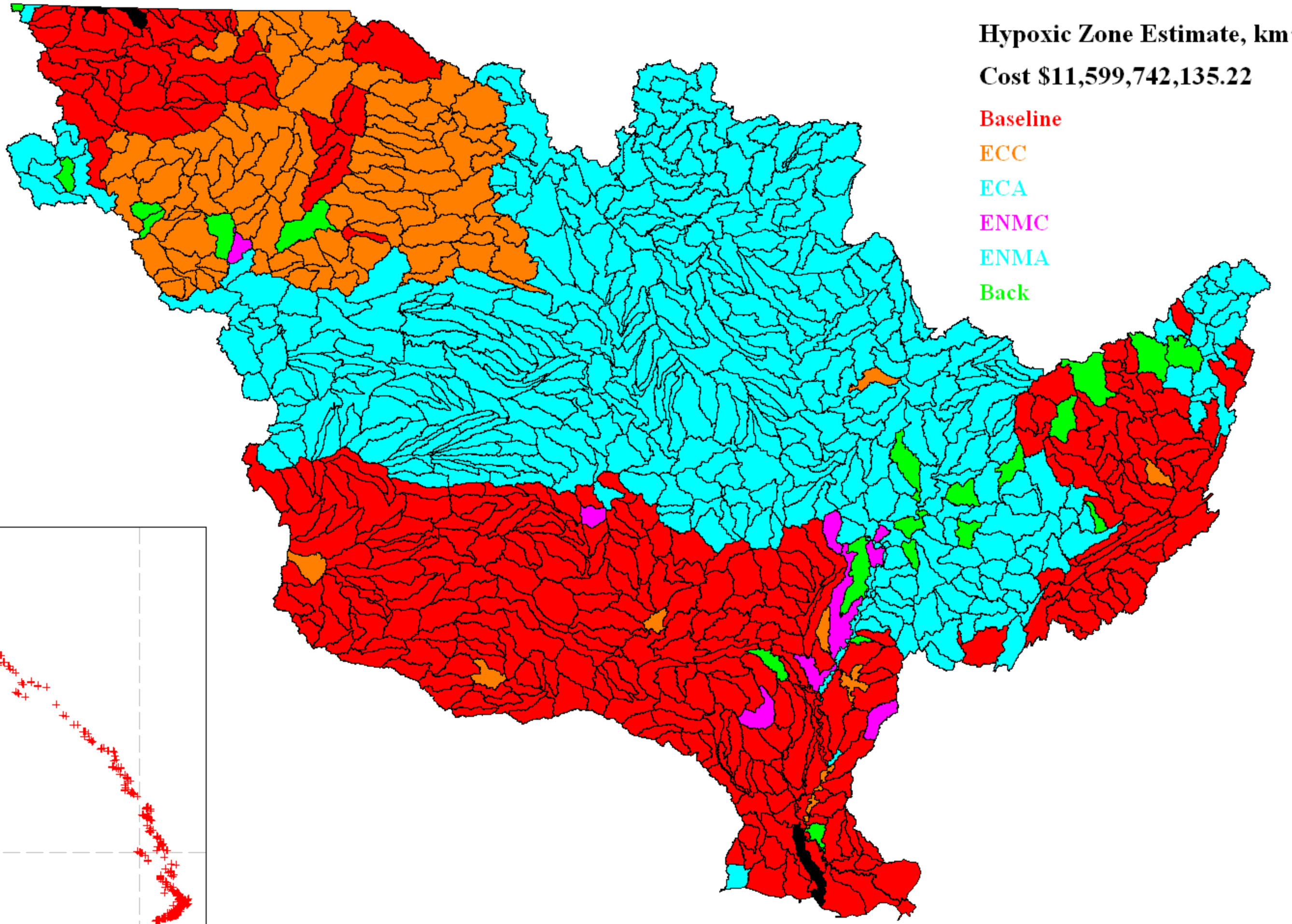


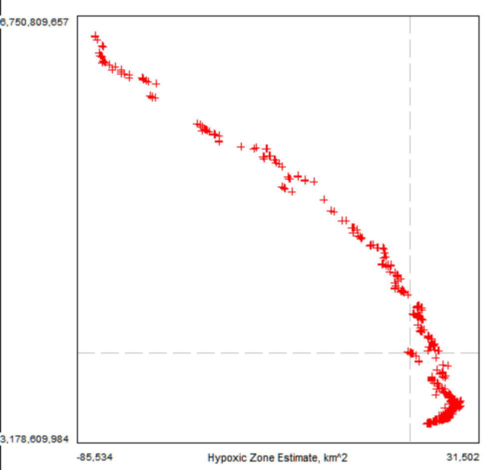
Similar zone size (2700 km2) at lower cost , $12.7 bn
Similar pattern of treatment location



Similar cost, $14.2 billion, but about ½ zone size

But, there are some solutions in the frontier which use working land practices more extensively





Results

1. Empirical model suggests importance of targeting both N and P and of "legacy" nutrients
2. Additional conservation investments can be effective in reducing the size of Gulf hypoxia
3. Proposed approach highlights potential priority watersheds
4. Agricultural production can be maintained and hypoxia addressed but costs not trivial
5. Highlights value of developing and refining new technologies to retain nutrients (bioreactors, tile drain management)

CARD

Major caveats

1. Modeling system ignores general equilibrium (market effects) effects associated with major land use change
2. Solutions target only dead zone, ignores all other ecosystem services- upstream water quality, habitat, biodiversity, carbon storage in soils, etc.
3. Newer technologies and innovation could change cost story a lot
4. No discussion of incidence – who finally pays