Least Cost Control of Agricultural Nutrient Contributions to Local Waters and the Gulf of Mexico Dead Zone

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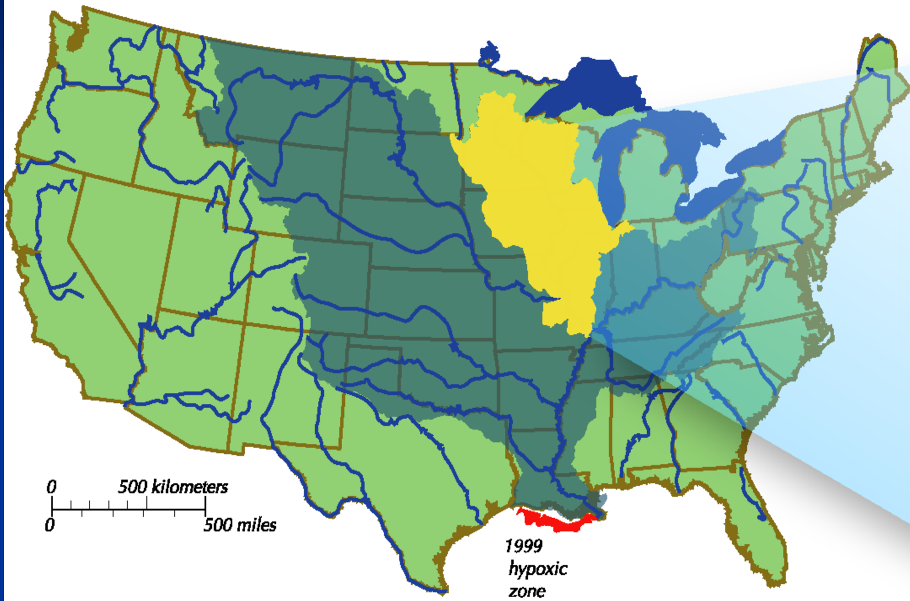
Outline

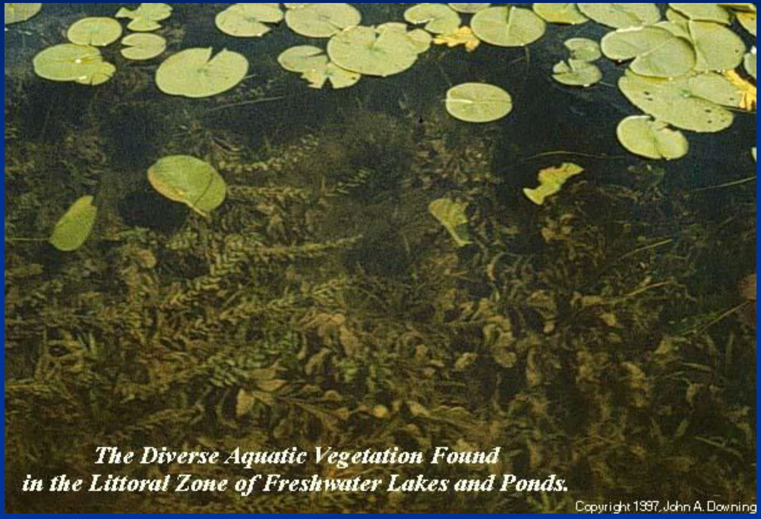
- Intro to water quality issues in the U.S. midwest
  - Local water quality
  - Gulf of Mexico hypoxic zone
- Agricultural conservation practices and nonpoint source pollution
- Economic problem of finding least cost solution to this nonpoint problem
- Empirical results of applying evolutionary algorithm with hydrologic simulation model

The UMRB: local water quality



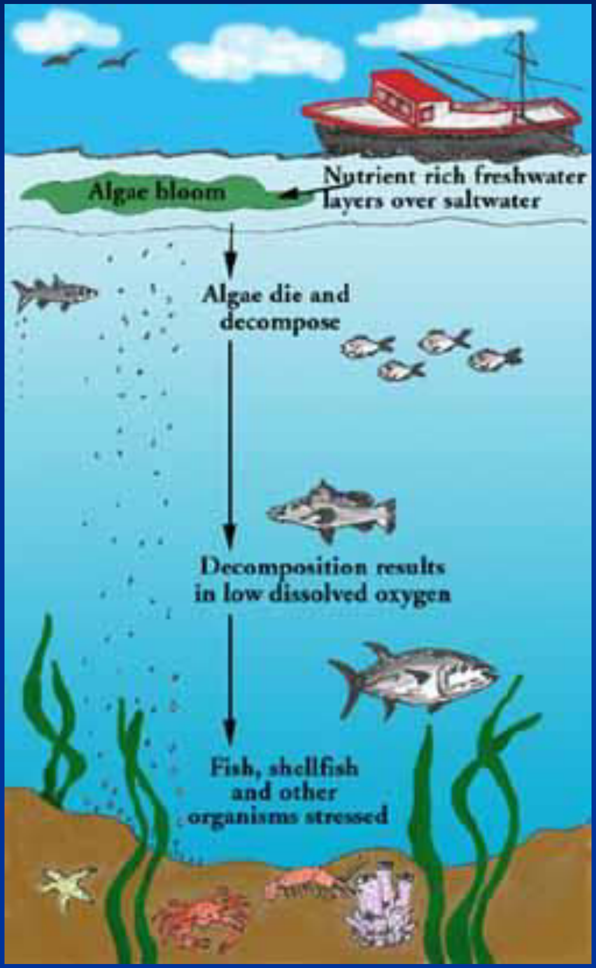
- 189,000 square miles in seven states,
- dominated by agriculture: 67% of total area,
- > 1200 stream segments and lakes on EPAs impaired waters list,
- highest concentrations of phosphorous found in the world

Local Water Quality



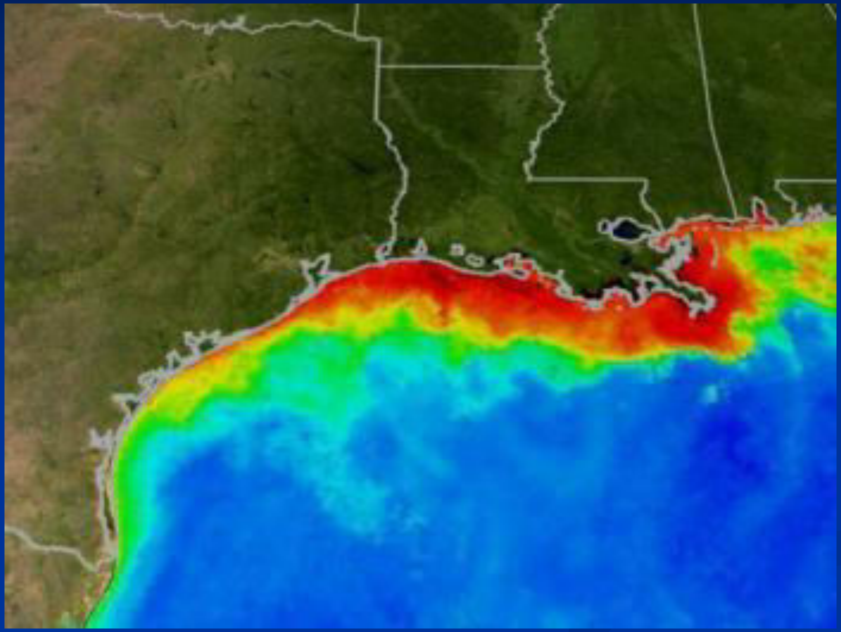
- Nutrients (esp. phosphorous) and sediment primary source
- Agriculture accounts for over 50% of impairments (EPA)
- Multiple conservation practices can ameliorate
  (Land retirement, conservation tillage, grassed waterways, contours, terraces)

Hypoxia = Dead Zone



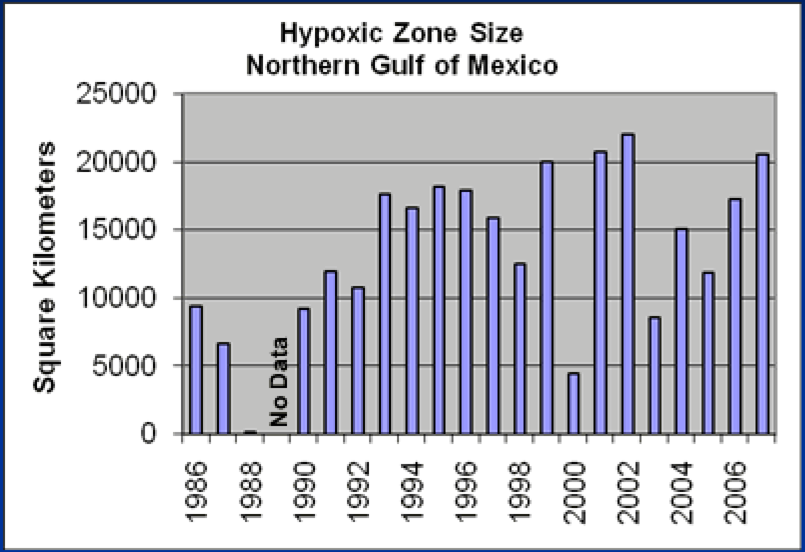
- 165 Hypoxic zones worldwide
- Naturally occurring, but far larger due to anthropogenic sources of nutrients
- Depleted oxygen creates zones incapable of supporting most life
- Potential evils: commercial fishing, recreation, ecosystem effects, habitat, etc.
- Effects quite poorly documented, information from other hypoxic zones relevant? Ecological "tipping point?"

Hypoxic zone in the Gulf of Mexico.



Summertime satellite observations of ocean color from MODIS/Aqua show highly turbid waters which may include large blooms of phytoplankton extending from the mouth of the Mississippi River all the way to the Texas coast. When these blooms die and sink to the bottom, bacterial decomposition strips oxygen from the surrounding water, creating an environment very difficult for marine life to survive in. Reds and oranges represent high concentrations of phytoplankton and river sediment. Image taken by NASA and provided courtesy of the NASA Mississippi Dead Zone web site.

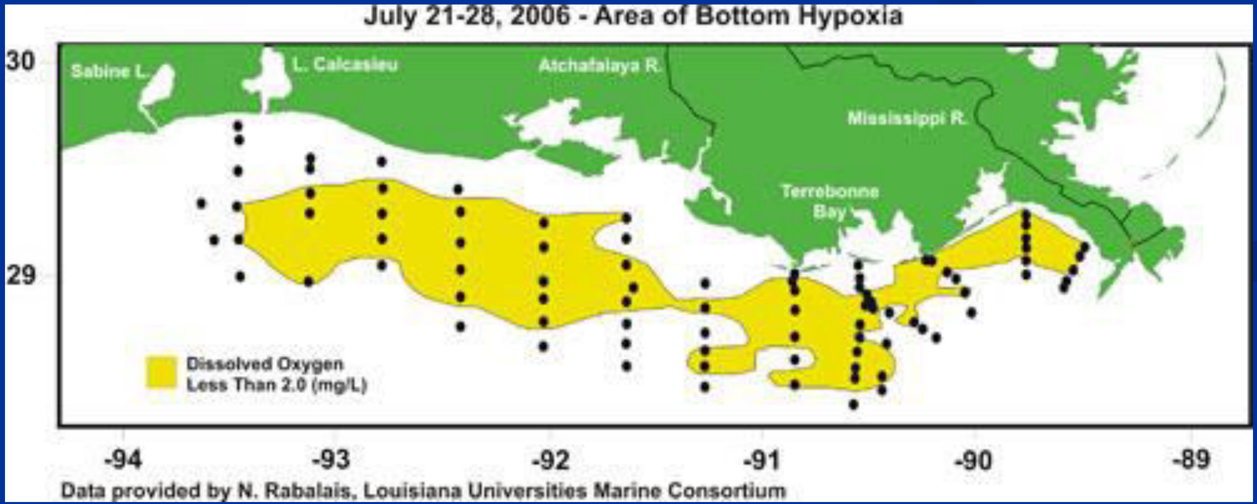
Gulf of Mexico Hypoxia



Source: Dr. Nancy Rabalais
Universities Marine Consortium

- Now, second largest worldwide

•4000 – 22,000 sq km



Gulf Hypoxia: Emission Sources

- Causes: nutrients from Mississippi river, nitrates and phosphorous,

- Limiting nutrient may now be P (scientific debate continues)

- Major Contributors:

    - UMRB (1+2) = 43%N, 41%P

    - Ohio-Tennessee (6+7) = 41%N, 59%P

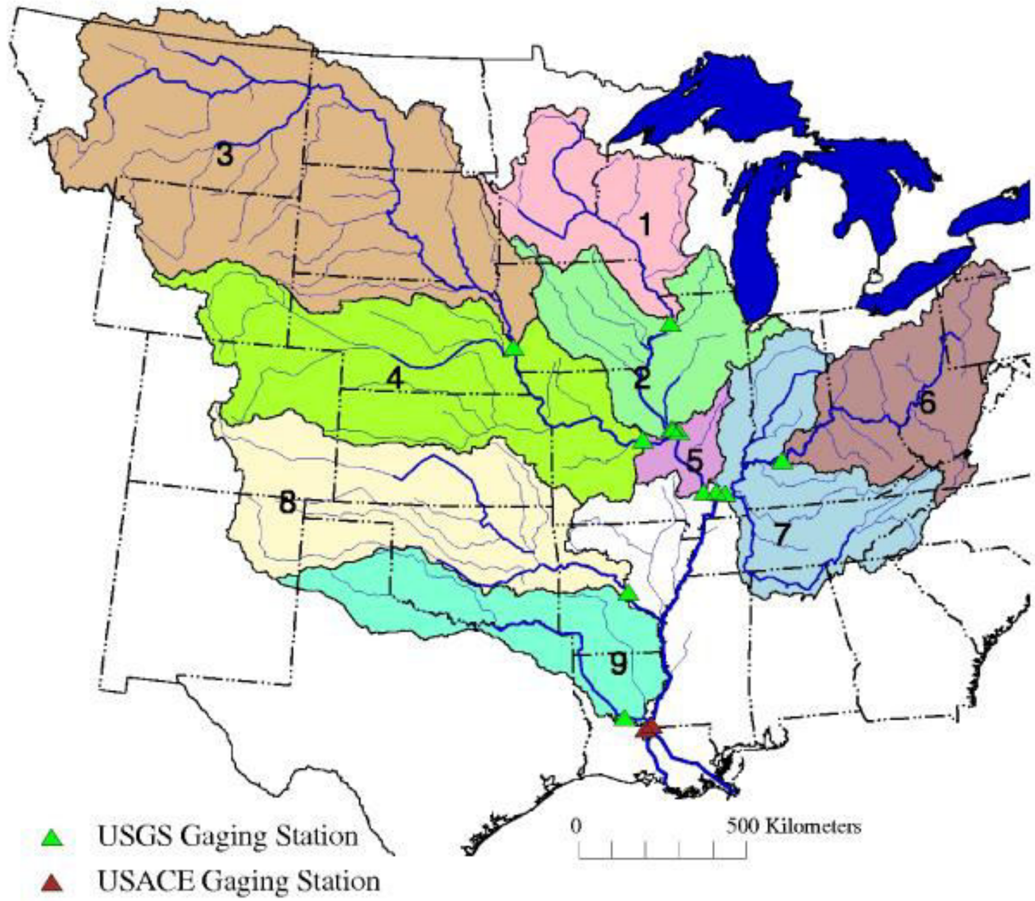


Figure 2. Location of nine large subbasins comprising the Mississippi-Atchafalaya River Basin that are used for estimating and studying nutrient fluxes.

USGS

USGS Open-File Report 2007-1080

http://toxics.usgs.gov/pubs/of-2007-1080/methods_large_subbasins.html

Examples of conservation practices

- Terraces: an earth embankment, or a combination ridge and channel, constructed across the field slope (USDA-NRCS)
- Grassed waterways: natural or constructed channel with suitable vegetation
- Contour farming: tillage, planting, and other farming operations performed on or near the contour of the field slope
- No-till: managing the amount, orientation and distribution of crop and other plant residue on the soil surface year round while limiting soil-disturbing activities to only those necessary to place nutrients, condition residue and plant crops
- Land retirement (CRP): remove land from working production, plant with perennial grasses or other appropriate vegetation
- Nutrient management: reduced fertilization, N

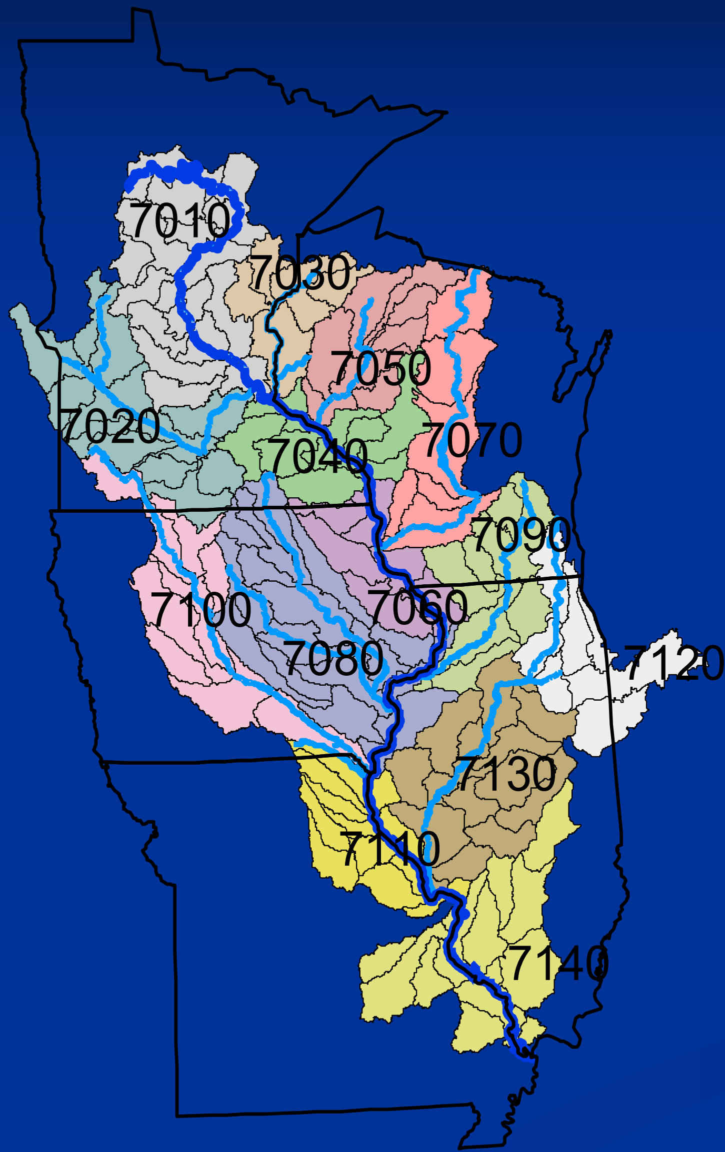
Conservation practices

- Photos courtesy of USDA NRCS

Integrated Economic, Land use, and Water Quality Model for the UMRB

- Couple large-scale, spatially-detailed watershed model with economic model to study costs and water quality changes of conservation policy
- Focus on agricultural land use decisions – cropland
- Use NRI as basis for both economics and watershed model (110,000 total "points" and expansion factors, 37,500 cropland observations)
- Purpose of modeling system is to provide policy level information
- Consider both upstream water quality (within the UMRB), and downstream effects (Gulf of Mexico)

Key Watershed Features



Features of the 4 Digit HUCs				
4 Digit HUC	Total NRI points	Total area millions of acres	% total area cropped	Average CRP rental rates
7010	8954	1.2	18	52
7020	7797	0.92	69	91
7030	4113	0.46	10	35
7040	6495	0.65	33	78
7050	3847	0.55	11	40
7060	5930	0.55	42	122
7070	5141	0.66	14	73
7080	14965	1.46	67	128
7090	7167	0.66	56	121
7100	8375	0.9	64	116
7110	5883	0.59	44	69
7120	7661	0.63	55	116
7130	9745	1.13	72	129
7140	7776	0.79	44	79

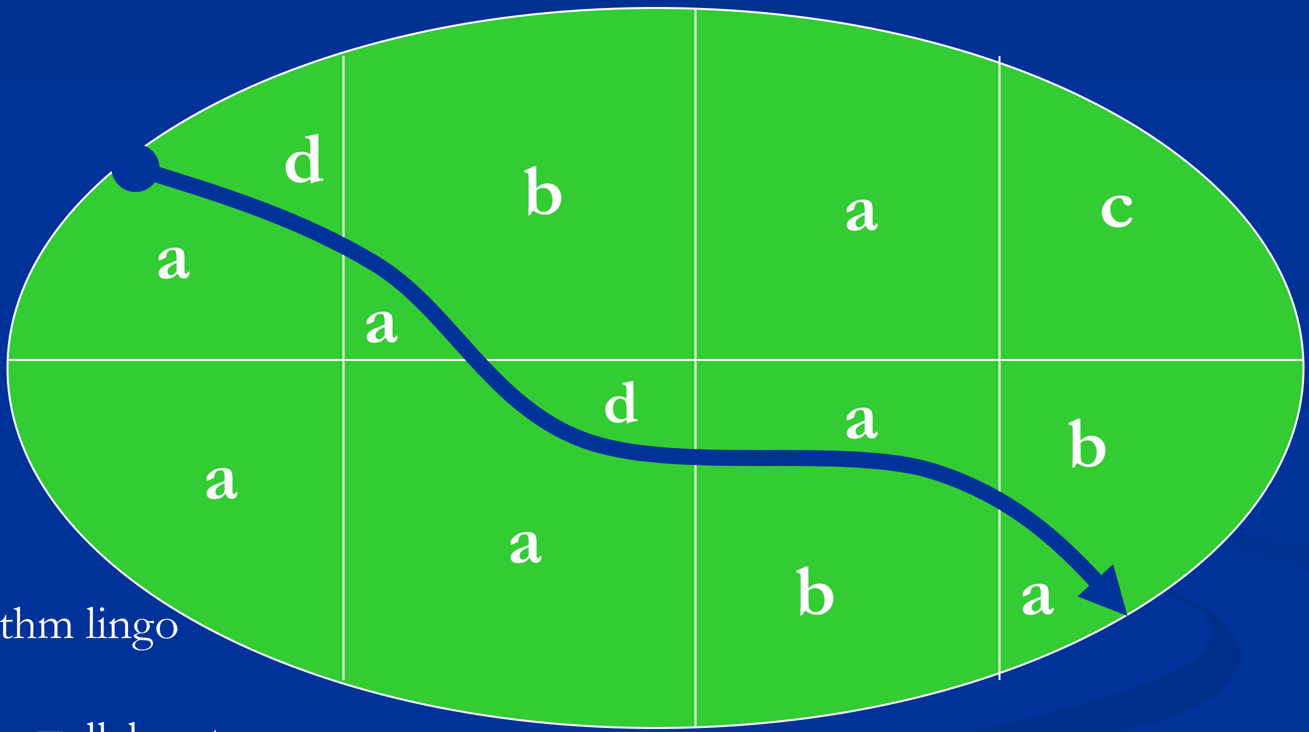
Least Cost Problem

- One field's pollution damage affected by choices on other fields
  - no exogenous "delivery coefficients"
  - non-mutually exclusive CP's can be implemented on any field, different effectiveness and costs
  - precludes simple spatial optimization schemes
- Brute force
  - using hydrologic model, analyze all the feasible scenarios, picking cost-efficient solutions
  - But, if there are N conservation practices possible for adoption on each field and there are F fields, this implies a total of possible N^F configurations to compare
  - 30 fields, 2 options → over 1 billion possible scenarios

Multiobjective optimization evolutionary algorithms

- provide a way to search for Pareto-optimal sets
- SPEA2 (Strength Pareto Evolutionary Algorithm 2) (Ziztler and Thiele, 2001) is used
- Of the three objectives (N, P, Cost), only cost can be easily computed for a particular scenario, nutrient loadings need to be simulated
- Combine:
  - An evolutionary algorithm, SPEA2
  - Hydrologic model, Soil and Water Assessment Tool (SWAT)
  - Sometimes referred to as *simulation-optimization* framework

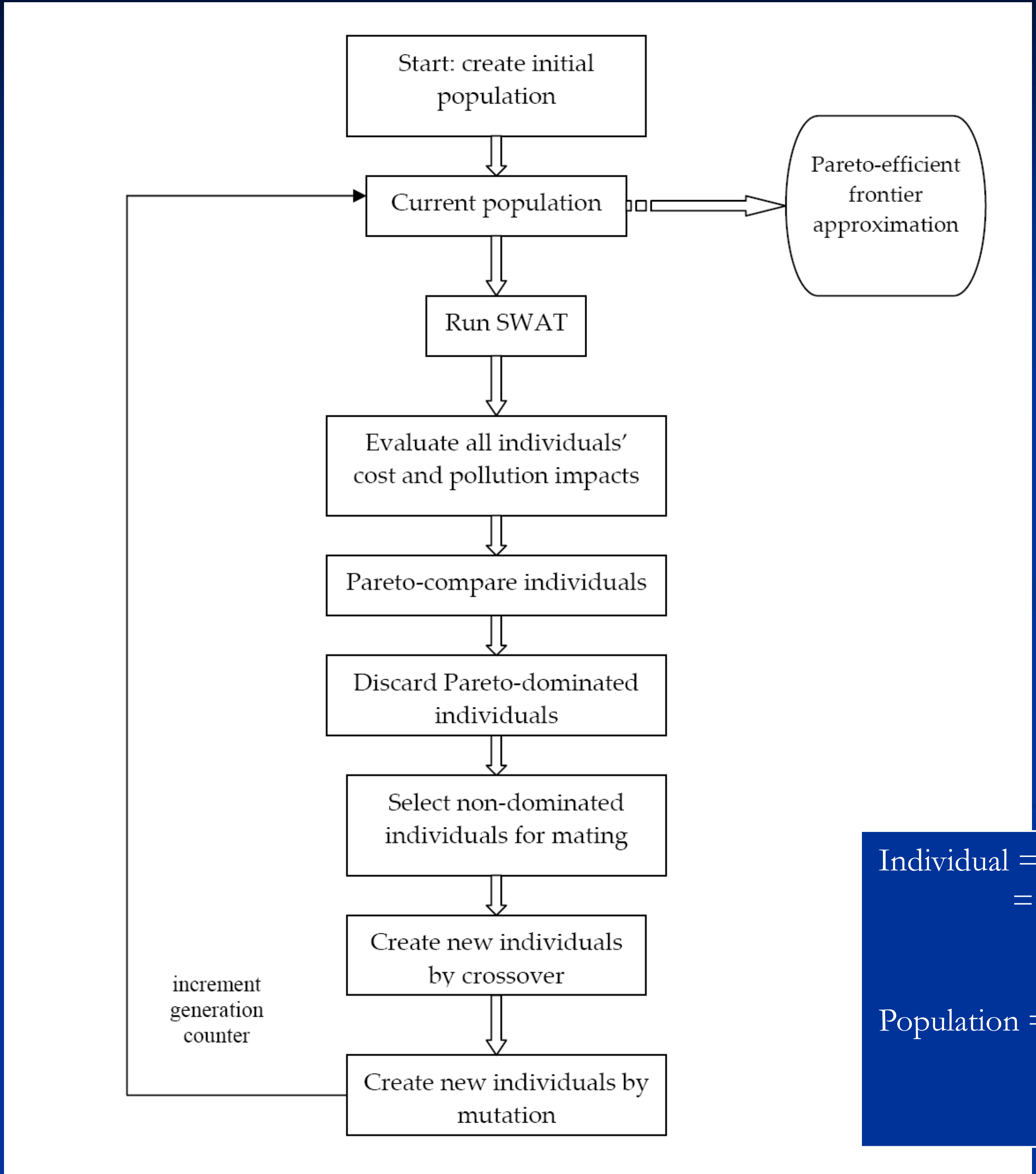
One possible watershed configuration



Genetic Algorithm lingo
Field = gene
Practice options =allele set
watershed configuration = individual (described
by set of genes)
Population = set of configurations

13 Fields
4 conservation practices
13^4=28561 possible configurations

Algorithm flow diagram

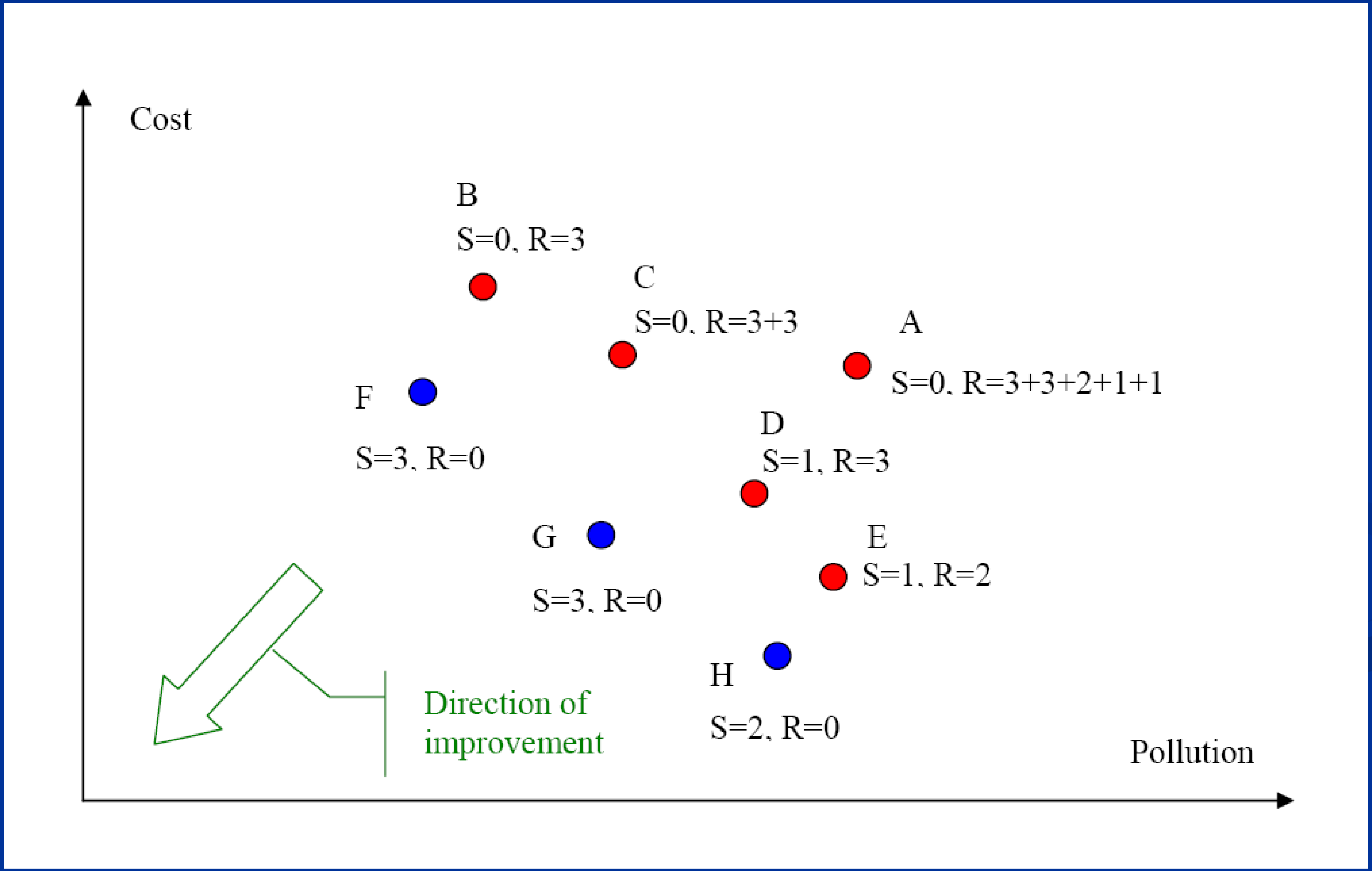


Individual = watershed configuration
= specific assignment of practices to fields

Population = set of watershed configurations

Fitness assignment example

- Strength S(*i*) = # of individuals *i* dominates
- Raw fitness R(*i*) = sum of strengths of individuals that dominate *i*



Soil and Water Assessment Tool (SWAT)

- A hydrologic and water quality model developed by the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS)
- A long-term continuous watershed-scale simulation model that operates on a daily time step and is designed to assess the impact of different management practices on water, sediment, and agricultural chemical yields
- Gassman et al. (2007) identify over 250 publications using SWAT

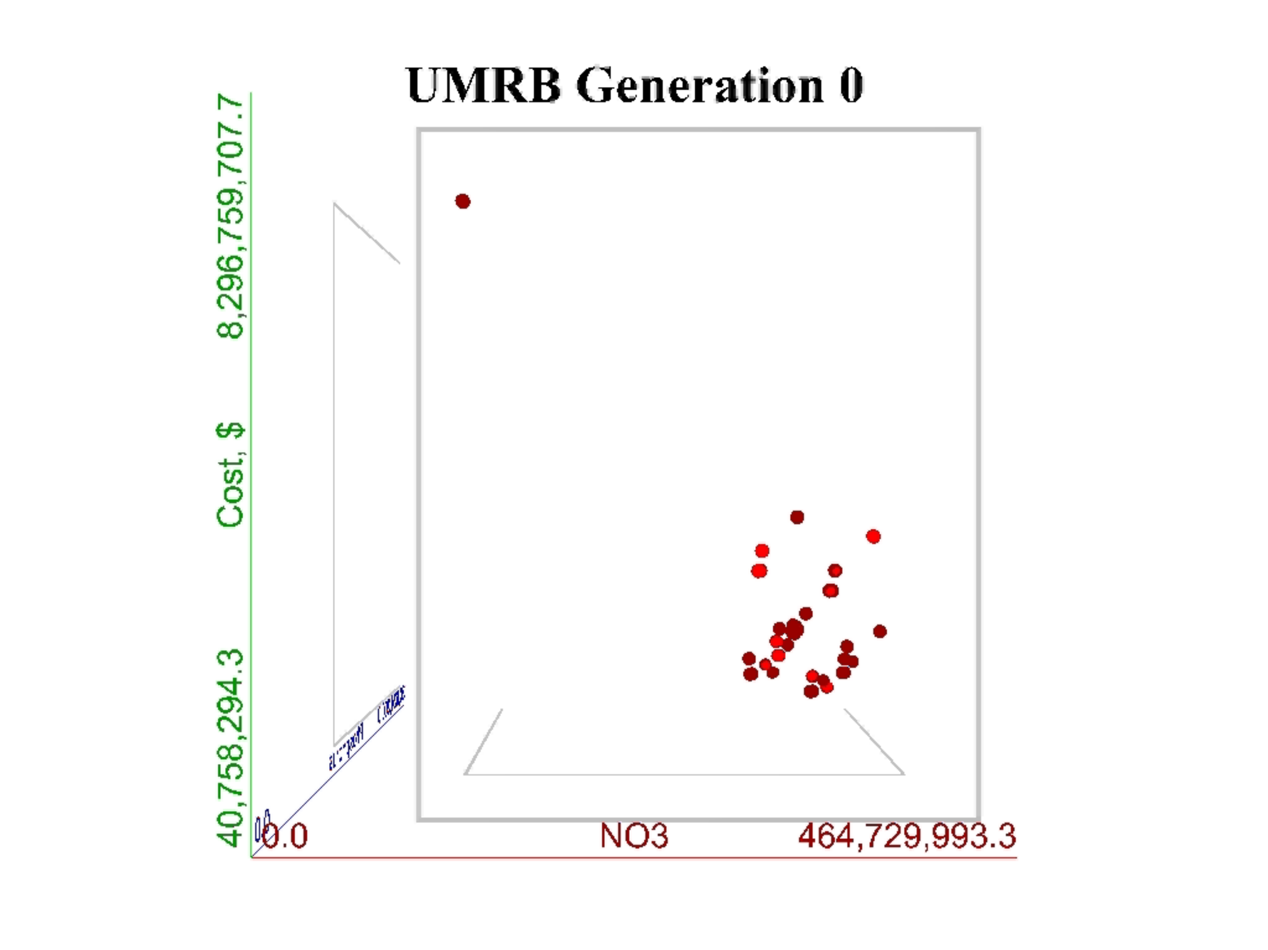
The conservation practices set

- For each hydrologic unit in the watershed, consider 1 of 33 mutually exclusive options
- One is land retirement
- Obtain the rest of options by interacting 4 tillage types (CT, RT, MT, NT) with
  - Practices:
    - Terraces
    - Contouring
    - Grassed Waterways
  - 20% N fertilizer reduction
- Baseline conservation practices impose a set of constraints
  - In this application, algorithm only allowed to add practices

Costs of practices

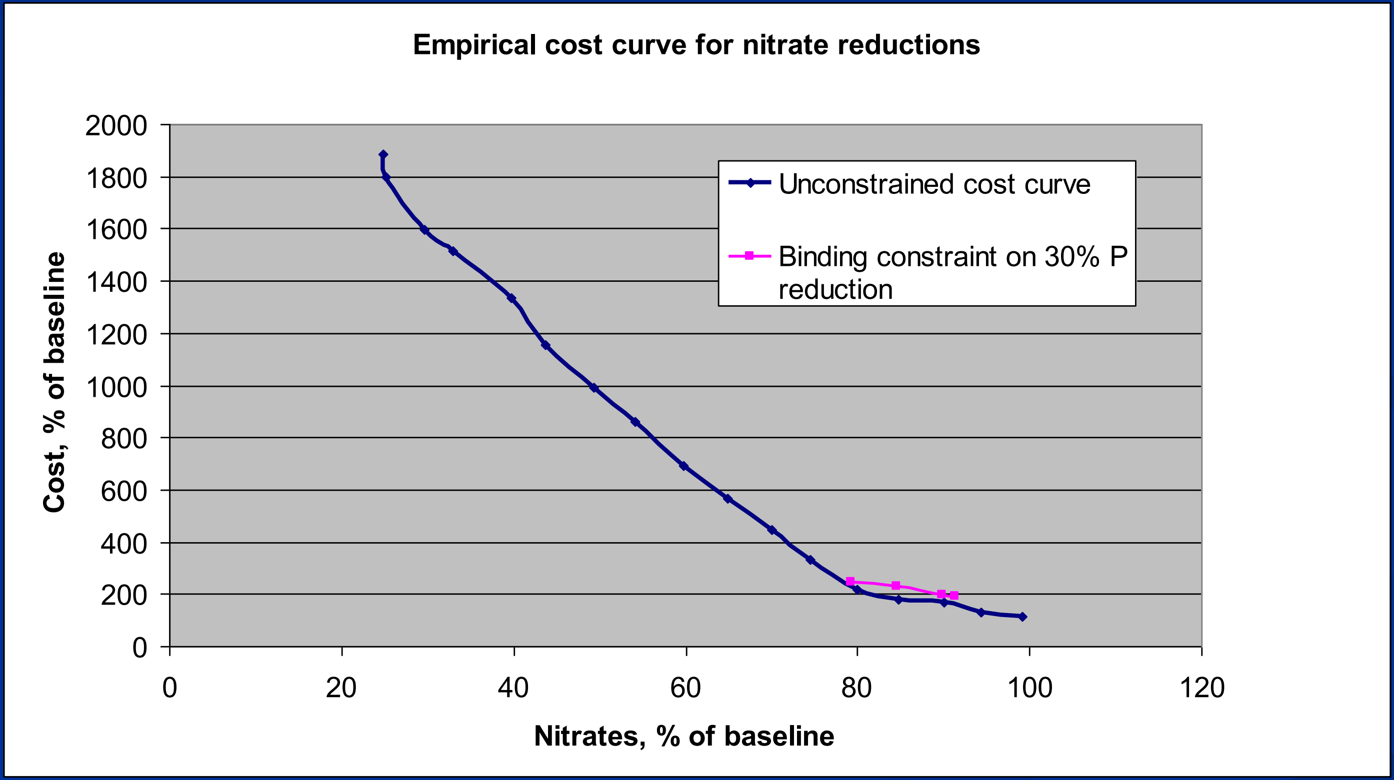
- Sources of information on the cost of CP's:
  - Terraces, Grassed Waterways, Contouring, No-Till:
    - EQIP: Federal Conservation Program
    - IFIP: State Conservation Program
    - CRP: Federal Conservation Program
  - Land retirement: 2007 Iowa Cash Rental Rates Survey
- Costs of CP's vary by subbasin in each watershed
- Develop a cost estimate for fertilizer reduction
  - Approximate cost=Yield reduction*Corn price

Pareto frontier: UMRB



Tradeoffs of NPS control costs and water quality benefits

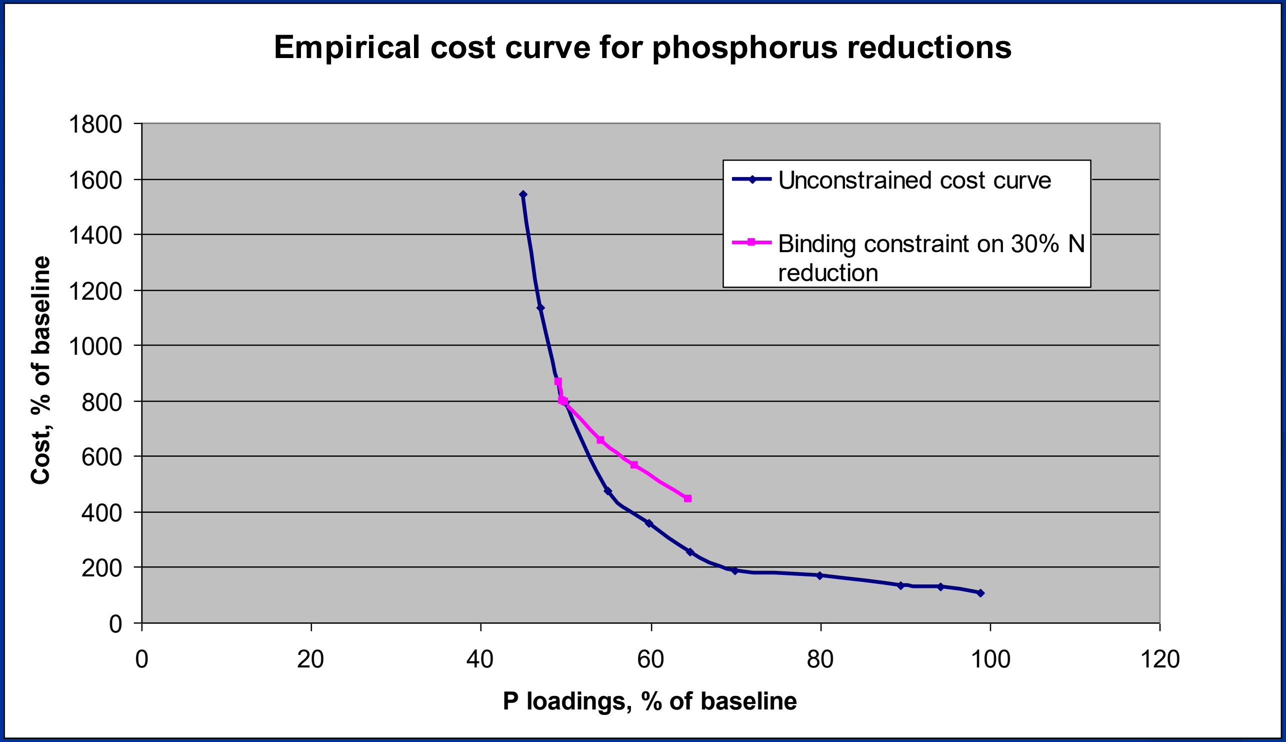
- Nitrate loadings at the outlet vs. costs



- Thus, if a policy seeks to reduce N by more than 20%, more than 30% reductions in P follow

Tradeoffs of NPS control costs and water quality benefits

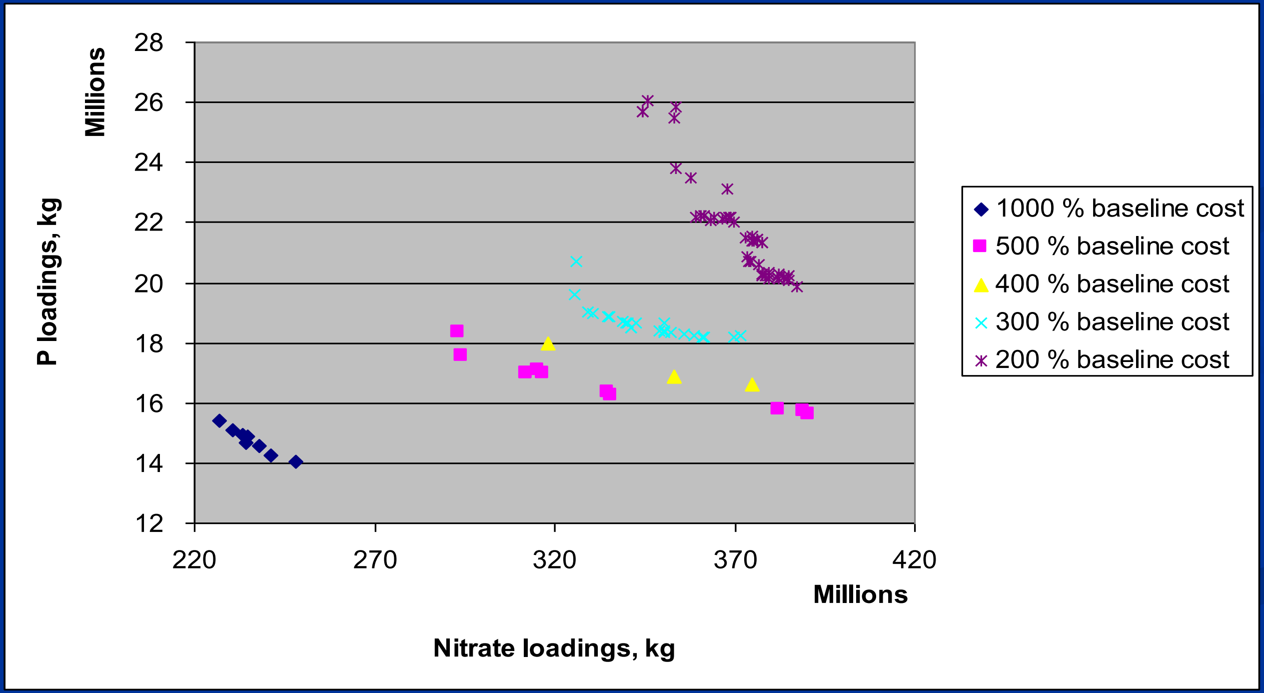
- Phosphorus loadings at the outlet vs. costs



- In this case, nitrate reduction constraint is binding up to a 50% reduction in P
- This suggests an asymmetry in the control of the two nutrients in the UMRB

Tradeoffs between pollutants (Nitrates and P)

- The frontier also highlights what nutrient reductions are feasible for a given budget
- As cost increases (to 10X the baseline), the scope of the tradeoff falls
  - reflects complementarities embedded in land retirement



A closer look at the frontier

- The frontier is also useful in answering how one can achieve specific pollution reduction targets
- For example,
  - Requiring a 30% reduction in outlet NO_3 automatically leads to a 35% reduction in outlet P
  - But: requiring a 30% reduction in outlet P leads only to a 9% reduction in outlet NO_3
- The annual additional cost is estimated to be:
  - $ 1.4 billion for reducing NO_3 by 30% (more than quadrupling baseline cost)
  - $ 370 million for reducing P by 30% (less than doubling the baseline cost)

What practices are selected?

4715: 30% N, 36% P	3821: 9% N, 30% P
Grassed Waterways 87% Reduced Fertilizer 89% Terraces 2% Reduced Tillage 58% Land Retirement 9% Cost = $1.4 billion/year	Grassed Waterways 91% Reduced Fertilizer 7% Terraces 1% Reduced Tillage 66% Land Retirement 0% Cost = $ 370 million/year

Conclusions

- The approach
  - Tries to fully account for the complexity of NPS pollution processes
  - Searches for efficient solutions to quantify tradeoffs
    - Between cost and pollution reductions
    - Between different pollutants
- As always, multiple caveats are in order
  - But the method is flexible and amenable to improvement