Nonpoint Source Pollution Control Programs: Enhancing the Optimal Design Using A Discrete-Continuous Multiobjective Genetic Algorithm

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Nonpoint Source Pollution

- Agriculture is among leading contributors to water quality impairments in the U.S. and around the world
- Control of agricultural NPS pollutants can be achieved through implementation of conservation practices, commonly known as best management practices (BMPs)
- Strategies for implementing conservation practices
  - Cost-share programs: a field-scale approach
  - Targeting critical areas within the watershed
    - Critical source areas
    - Scenario analysis
    - Optimization

Implementation of Conser. Practices

- Cost-sharing with land owners and producers
  - Does not guarantee maximum water quality benefits at the watershed scale
- Targeting using expert recommendations
- Targeting critical areas using geospatial characteristics of areas within the watershed, e.g., soil-topographic index
  - Important watershed processes and interactions amongst practices are not considered

Targeting Using Scenario Analysis

- Full enumeration and evaluation of all possible scenarios may be infeasible even at HUC 12 or similar scales.
- Employing optimization algorithms can facilitate identification of optimal suites of BMPs that reduce pollutant load at minimum cost.
- Multi-objective approaches can expose tradeoffs between often conflicting environmental, socioeconomic and institutional criteria.

Simulation-Optimization Approach

- ❑ Binary-variable optimization
- ❑ Discrete-variable optimization
- ❑ Continuous-variable optimization
- ❑ Mixed discrete/continuous-variable optimization

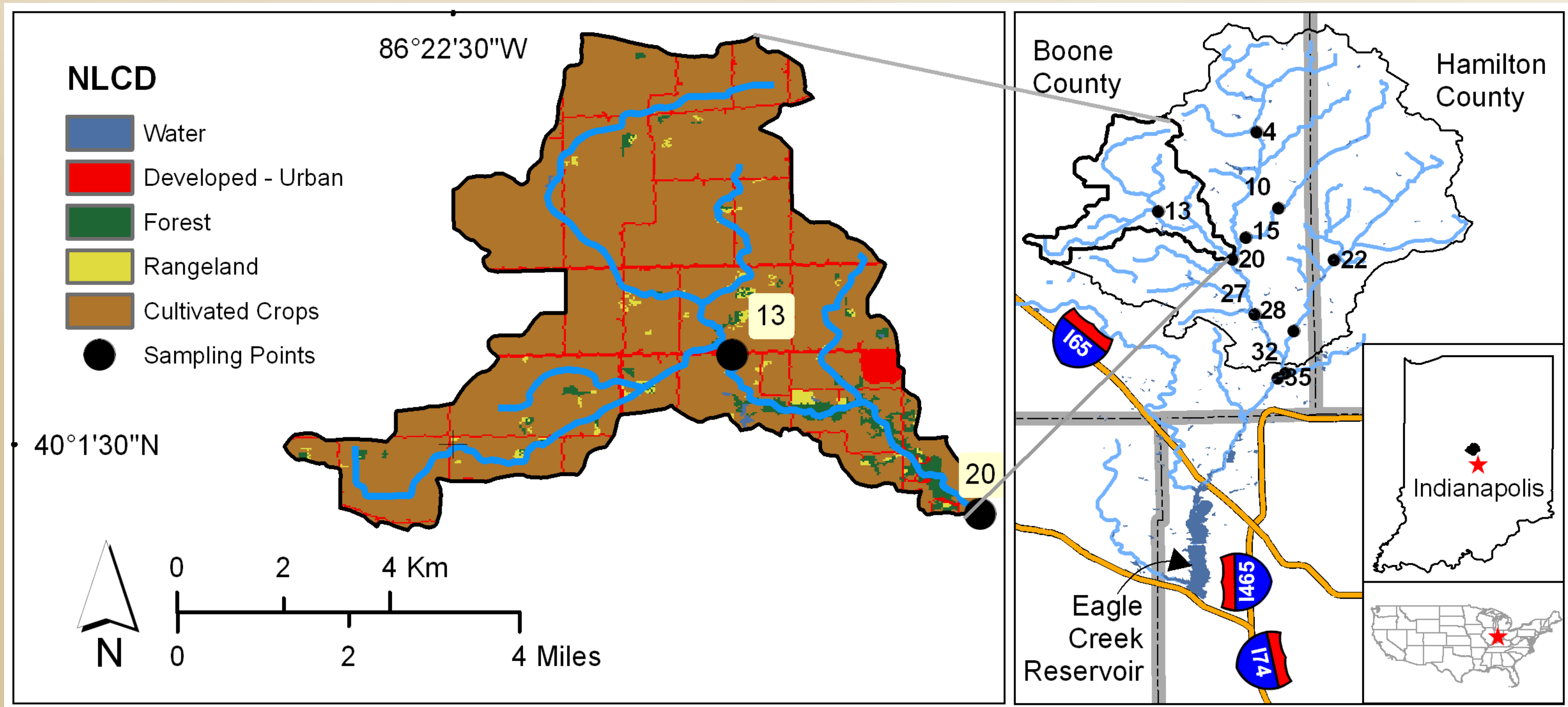
Study Objectives

- To develop a novel heuristic multiobjective optimization method using mixed discrete/continuous decision variables
- To determine improved assessment of environmental and economic tradeoffs using a mixed-variable optimization method compared to a binary optimization approach
- To examine enhanced convergence of the optimization approach by hybridization

Study Area

- Eagle Creek Watershed (ECW), Indiana

  Drainage area: 41.2 km^2



Calibration and Testing

- Simulation model: SWAT
- Special attention was paid to accurate representation of hydrologic and water quality processes

Gauging Station	Variable	Calibration Period Criteria (1995-1999)			Evaluation Period Criteria (2000-2004)		
		PBIAS (%)	R^2	NSE	PBIAS (%)	R^2	NSE
20	Monthly Nitrate	7.9	0.94	0.83	16.9	0.85	0.67
	Monthly Atrazine	-6	0.81	0.34	-14	0.7	0.41
22	Monthly Nitrate	-22.3	0.89	0.78	1.24	0.74	0.36
	Monthly Atrazine	42	0.69	0.44	-0.1	0.5	0.28
27	Monthly Nitrate	0.59	0.93	0.85	18.3	0.78	0.59
	Monthly Atrazine	13	0.66	0.35	-30	0.51	0.19
32	Monthly Nitrate	-7.9	0.92	0.84	8.4	0.76	0.55
	Monthly Atrazine	42.3	0.75	0.52	33.1	0.51	0.14
35	Daily Streamflow	-12.2	0.78	0.61	4.3	0.78	0.56

Multiobjective Optimization

- Method: Modified Nondominated Sorted Genetic Algorithm II (NSGA-II)

- Objective functions

$$\begin{cases} \text{minimize } y = f(\boldsymbol{x}|\boldsymbol{\theta}, I, t_d, T) & ;\text{Pollutant load(s)} \\ \text{minimize } C = g(\boldsymbol{x}|\boldsymbol{\theta}, I, p, r, t_d, T); & \text{Cost(s)} \end{cases}$$

- Constraint functions

$$\begin{cases} \text{Chance opf adoption} \\ \text{Management considerations} \end{cases}$$

Economic Component: Cost

$$C = C_0 + r_{OM} \times C_0 \left(\frac{1 - (1+i)^{-t_d}}{i} \right) + C_{OP}$$

C_0: implementation cost

r_{OM}: maintenance cost as a percentage of C_0

i: interest rate/100

t_d: design lifetime of the conservation practice (years)

C_{OP}: opportunity cost (eg. loss of crop production), expressed as

$$C_{OP} = \sum_{\mathrm{k}=1}^{\mathrm{K}} r_k \beta_k$$

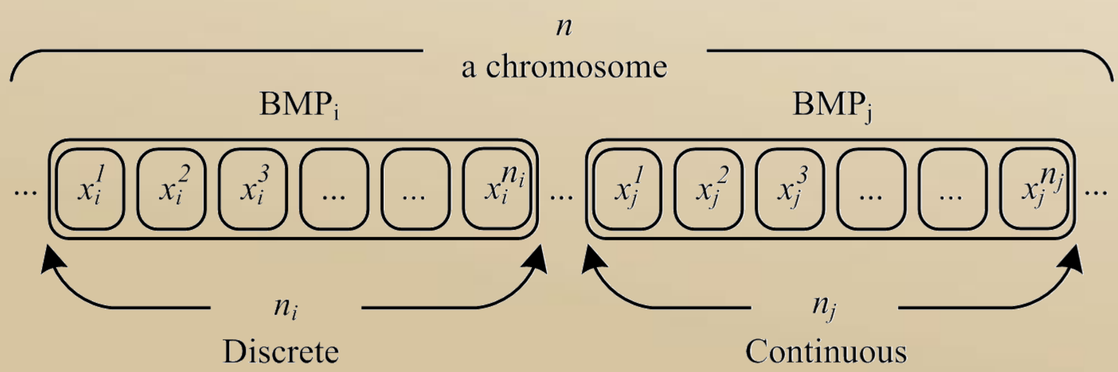
K: number of fields

r_k: unit price of crop in field k

β_k: changes in crop production

Mixed-variable optimization

	Field 1	Field 1	Field 1	…	Field *K*	Type
Practice 1	0|1	0|1	0|1	…	0|1	Binary
Practice 2	0|1	0|1	0|1	…	0|1	Binary
Practice 3	0|1|2|3	0|1|2|3	0|1|2|3	…	0|1|2|3	Discrete
Practice 4	0-20	0-20	0-20	…	0-20	Continuous



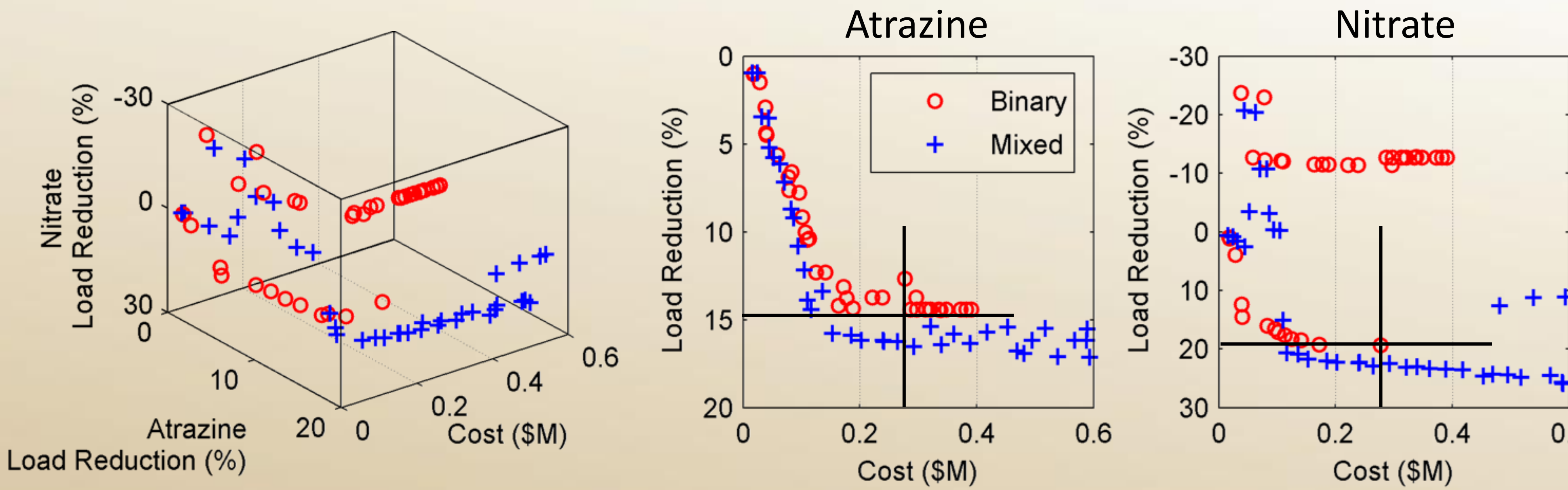
Representation of Conservation Practices

BMP	Parameter	Binary-variable	Mixed-variable
Fertilizer Management	Application rate reduction (%)	20	0-30 (Continuous)
Grassed Waterways	Width (m)	15	10, 15, 25 (Discrete)
Grade Stabilization	Height (m)	1.2	1.2 (binary)
Tillage/Residue management	Type	Conservation	Conventional Conservation No-till (Discrete)

Optimization Operation Parameters

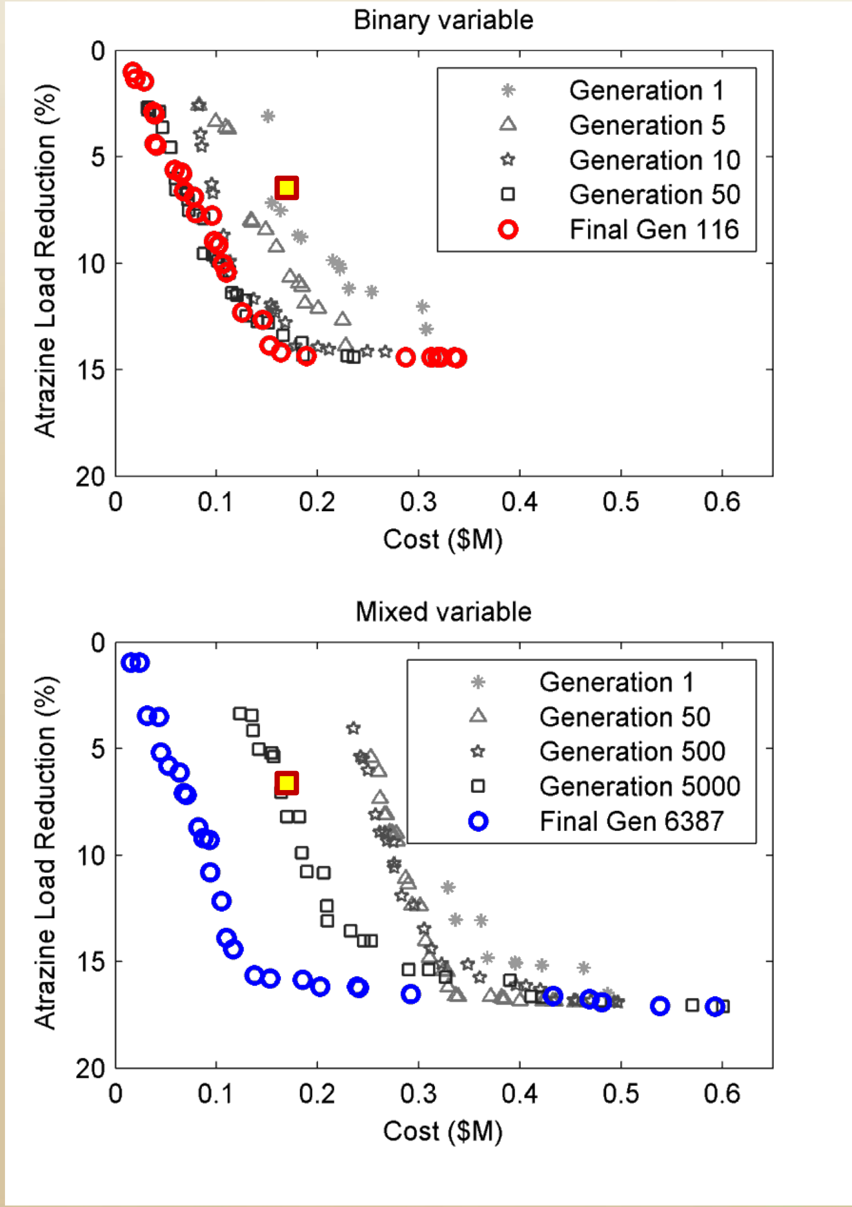
- Population size = 100+
  - Parallel runs
- Crossover probability = 0.5
- Mutation rate = 0.005
- Termination conditions: 30 consecutive runs with less than 0.01% improvement in objective function values and decision space

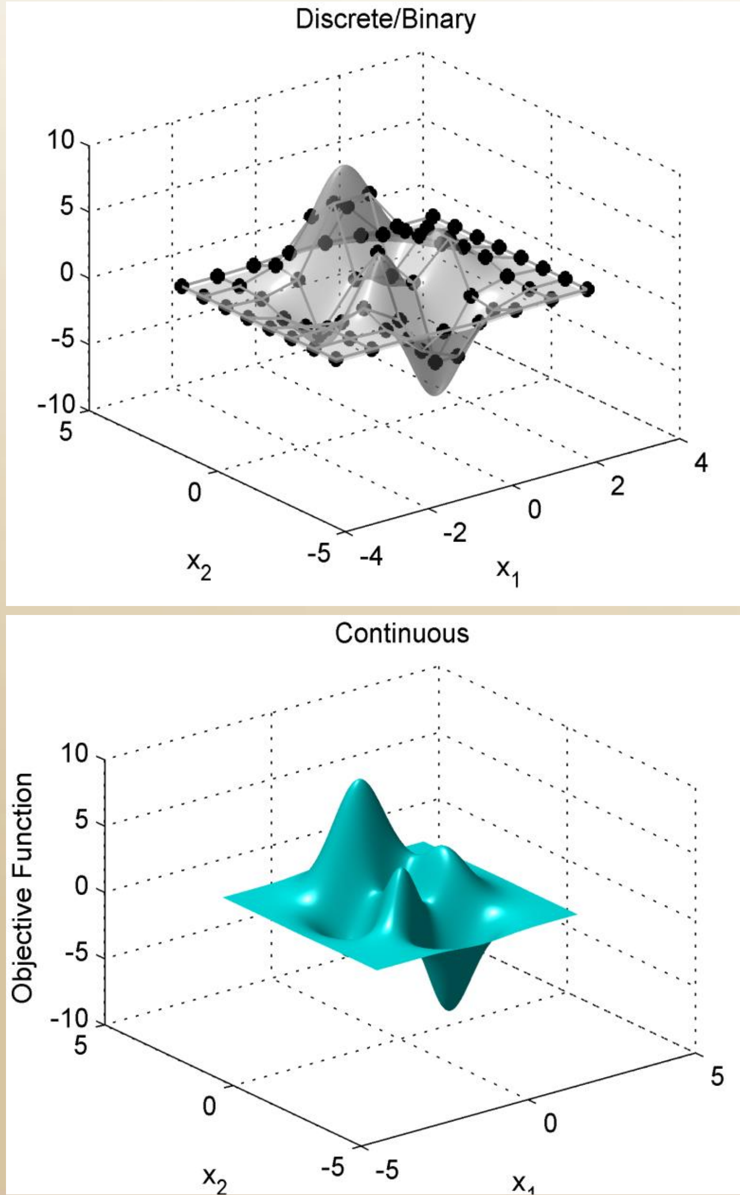
Results



- Mixed-variable approach improved load reduction by 20-25%
- Mixed-variable approach identified solutions with up to 40% lower cost for the same level of pollutant load reduction as compared to the binary-variable approach

Convergence



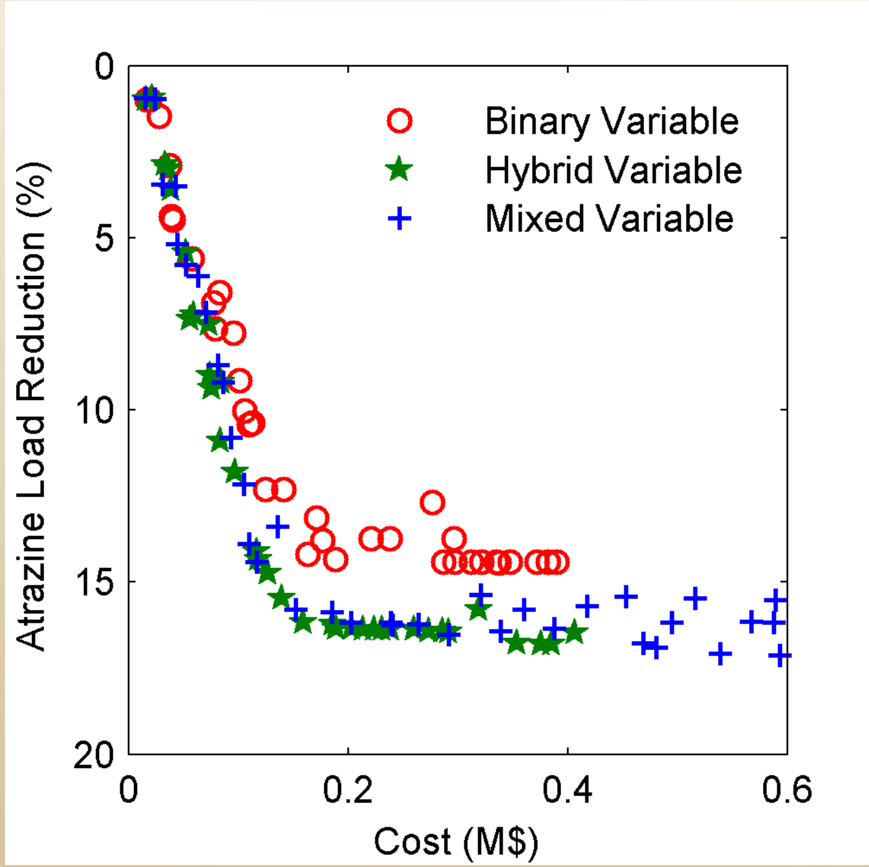


Hybridization

- Hybridization of modified GA with gradient-based local search method
  - GA-based optimization methods guarantee “convergence" but not “optimality"
  - Does not work with discrete-variables problems

Enhanced Convergence by Hybridization

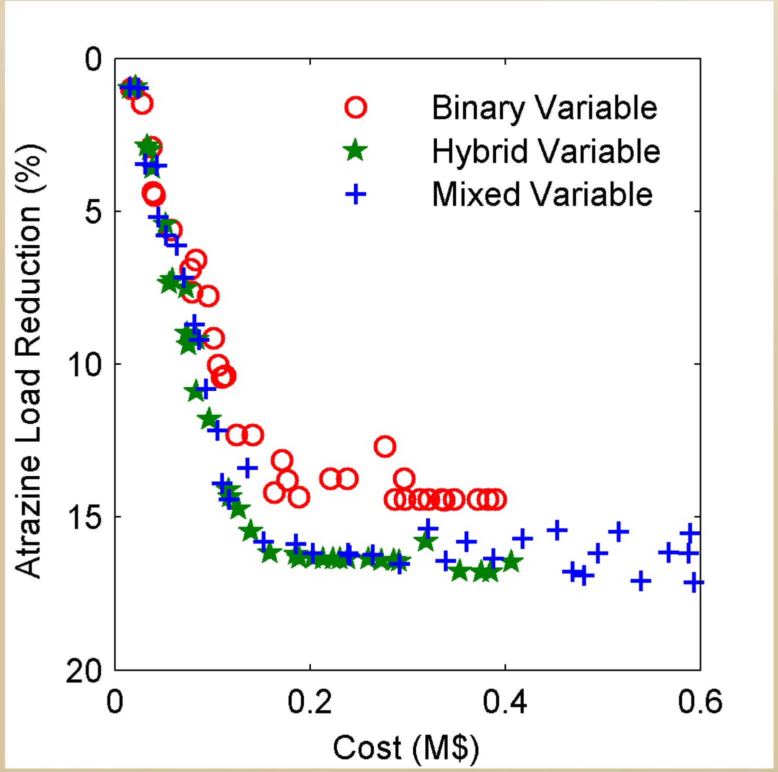
- The Hybrid method terminated in 66 generations after the binary optimization solutions were identified
- Nearly 30 times faster than the mixed-variable NSGA-II

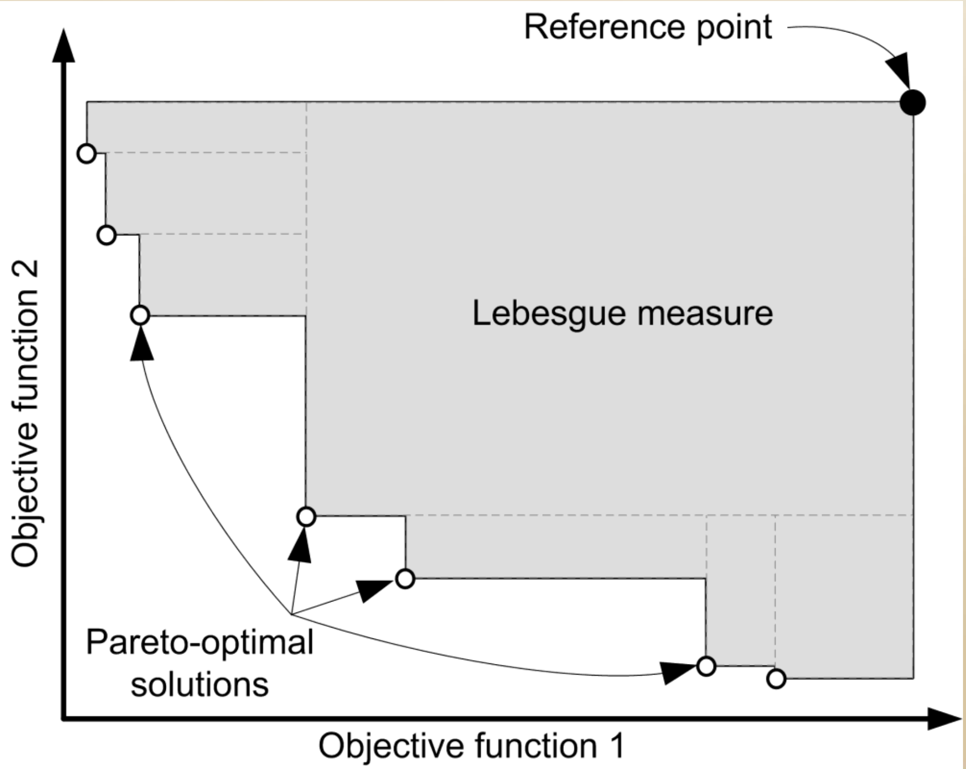


Comparison of the objective space

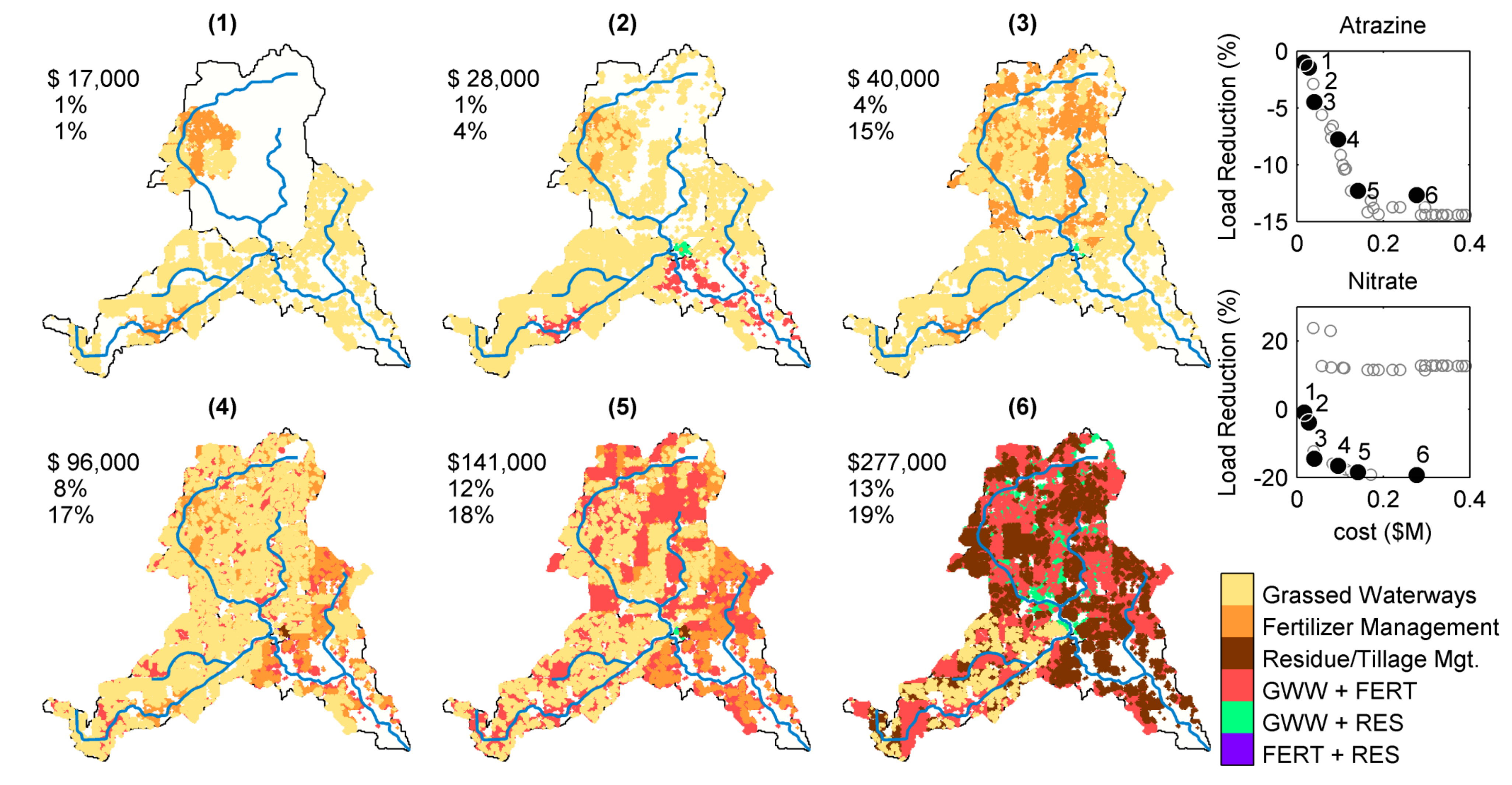
- Lebesgue measure (*n*-dimensional volume)

Algorithm	Lebesgue Measure
Binary	4.54×10^8
Mixed	5.71×10^8
Hybrid	5.78×10^8





Spatial Distribution of Practices



Additional Notes

- Priority BMPs
  1. Grassed waterways
  2. Fertilizer management
  3. Residue/tillage management

- Tillage/residue management had inverse impact on nitrate load in most of the fields and received the lowest priority

Conclusion

- Tradeoffs between maximizing environmental benefit/load reduction and minimizing Costs are apparent, hence, multi-objectve optimization is an effective tool for prioritization of fields and practices on a HUC 12 or similar scales

- Mixed-variable optimization identified better solutions than binary-variable approach

- Hybrid algorithms can significantly decrease runtime for complex discrete-continuous optimization problems