

Quantifying Co-Benefits of Water Quality Policies: An Integrated Assessment Model of Land and Nitrogen Management

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The Low Benefits of U.S. Water Quality Policy

- Keiser and Shapiro, 2019

	<i>Surface water (1)</i>	<i>Drinking water (2)</i>	<i>Air (3)</i>	<i>Greenhouse gases (4)</i>	<i>All other (5)</i>	<i>All (6)</i>
A: Total US expenditures (trillions of 2017 dollars)						
1970 to 2014	2.83	1.99	2.11	–	–	–
1973 to 1990	0.94	0.49	0.85	–	–	–
B: Estimated benefits and costs of regulations analyzed in years 1992–2017						
Total benefits / total costs	0.79	4.75	12.36	2.98	1.97	6.31
Mean benefits / mean costs	0.57	8.26	15.18	3.64	21.79	16.17
Share with benefits < costs	0.67	0.20	0.08	0.00	0.19	0.15

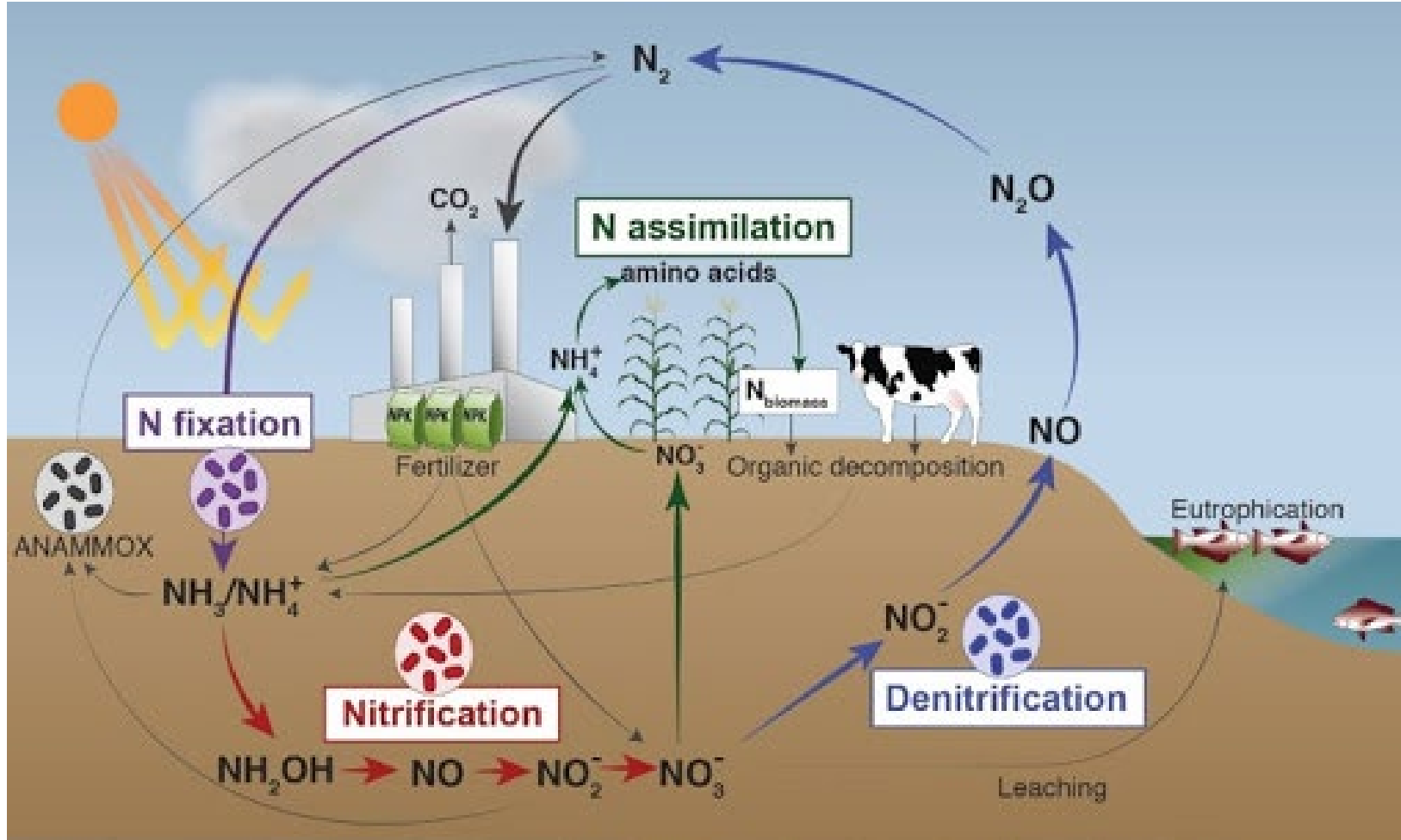
Missing Categories of Benefits

- Keiser, Kling, and Shapiro, 2019
 - Health benefits
 - Existence values
 - Non-standard pollutants
 - Certain types of resources
 - Reductions in Greenhouse Gas Emissions

Agriculture, Water Quality, and Climate Change

- In U.S., agricultural pollution is the top source of contamination in rivers and streams
- Agriculture also contributes a significant share of the greenhouse gas emission that cause climate change-17% directly through agricultural activities and an additional 7-14% through land use change

Agricultural Production, N Cycling, and Water Quality



Nitrogen applied in the form of commercial fertilizer

- A key input for agricultural production
- Degrades water quality, contributes to the eutrophication of surface water bodies, contaminate drinking water supplies
- Contributes to climate change as excess nitrogen is emitted in the form of nitrous oxide

Quantifying Co-benefits is Necessary

- Due to the nature of nitrogen cycling and the joint production of pollutants
 - Water policies designed to address water quality concerns have the potential to provide benefits beyond water quality improvements, such as reducing GHG emissions
 - “co-benefits”: the effects that are favorable to human welfare but incidental to the regulation’s intended target
- Current Literature on Quantifying Co-benefits
 - Mainly focus on the climate change mitigation policies
 - e.g., Ürge-Vorsatz et al. 2014; Nemet et al. 2010; Thompson et al. 2014
 - Only one study focus on water quality
 - Gasper et al. 2012 described the climate co-benefits in the context of water quality trading

Rationales for Quantifying Co-benefits

- Quantifying co-benefits is necessary for informing policy-makers about the potential effects of the regulatory action
- Not accounting for co-benefits would understate the benefits of fertilizer use reductions and drives a wedge between the regulated and socially optimal levels of nitrogen applications
- If these ancillary benefits are significant enough, then perhaps the outcomes of benefit-cost analysis would be altered
- The amount of co-benefits could serve as an incentive for environmental improvements and could be critical to establishing efficient and effective environmental markets

This Paper

- Develops an integrated modeling framework to quantify the co-benefits from emissions reductions that are generated by water policy to limit nitrate leaching from agriculture
 - Tightly couples an economic simulation model of agricultural decision making (land and fertilizer use) with an agronomic model of terrestrial nutrient cycling
 - Captures the feedback loops among farmer decision making, crop yields, and the joint production of nitrate and nitrous oxide
 - Accounts for N cycling in the simulation of nutrient leaching and GHG emissions levels

Water Quality Policies



**Land-Management
decisions
(Economic
optimization)**

Crop Yield



**Agricultural
Practices**



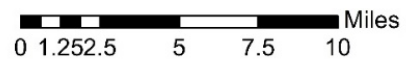
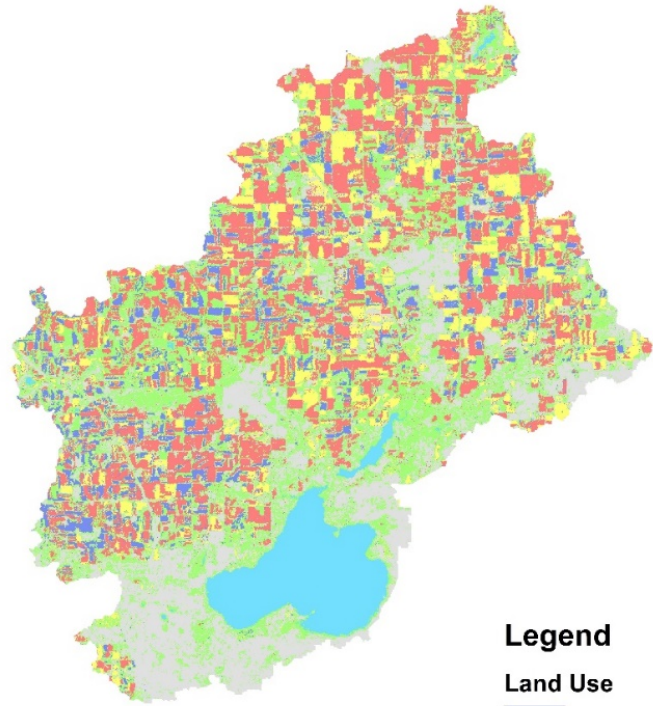
**Terrestrial
nutrient cycling
(Cycles/Biome-
BGC)**

Study Site: Lake Mendota Watershed, WI









- Dominated by agriculture (67% of the total land area)
- Current and historic agricultural land-management decisions in this catchment are the primary drivers of ongoing water quality concerns in the region
- There is a clear need to understand how policy tools could be used to adjust water quality concerns and to assess the benefits and costs of different policy options

Year: 2003

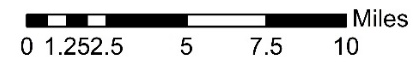
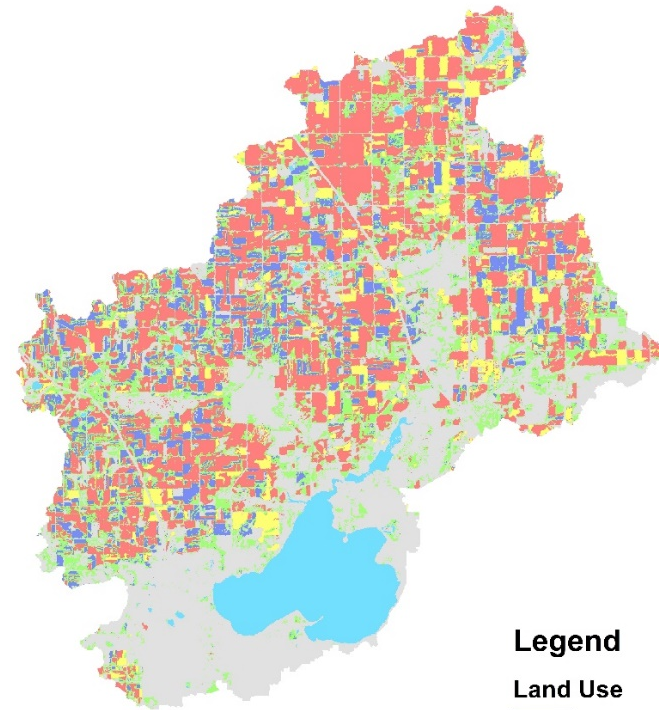


Legend

Land Use







-  Alfalfa
-  Corn
-  Grassland/Pasture
-  Soybeans
-  Other
-  Water

Year: 2014



Legend

Land Use

-  Alfalfa
-  Corn
-  Grassland/Pasture
-  Soybeans
-  Other
-  Water

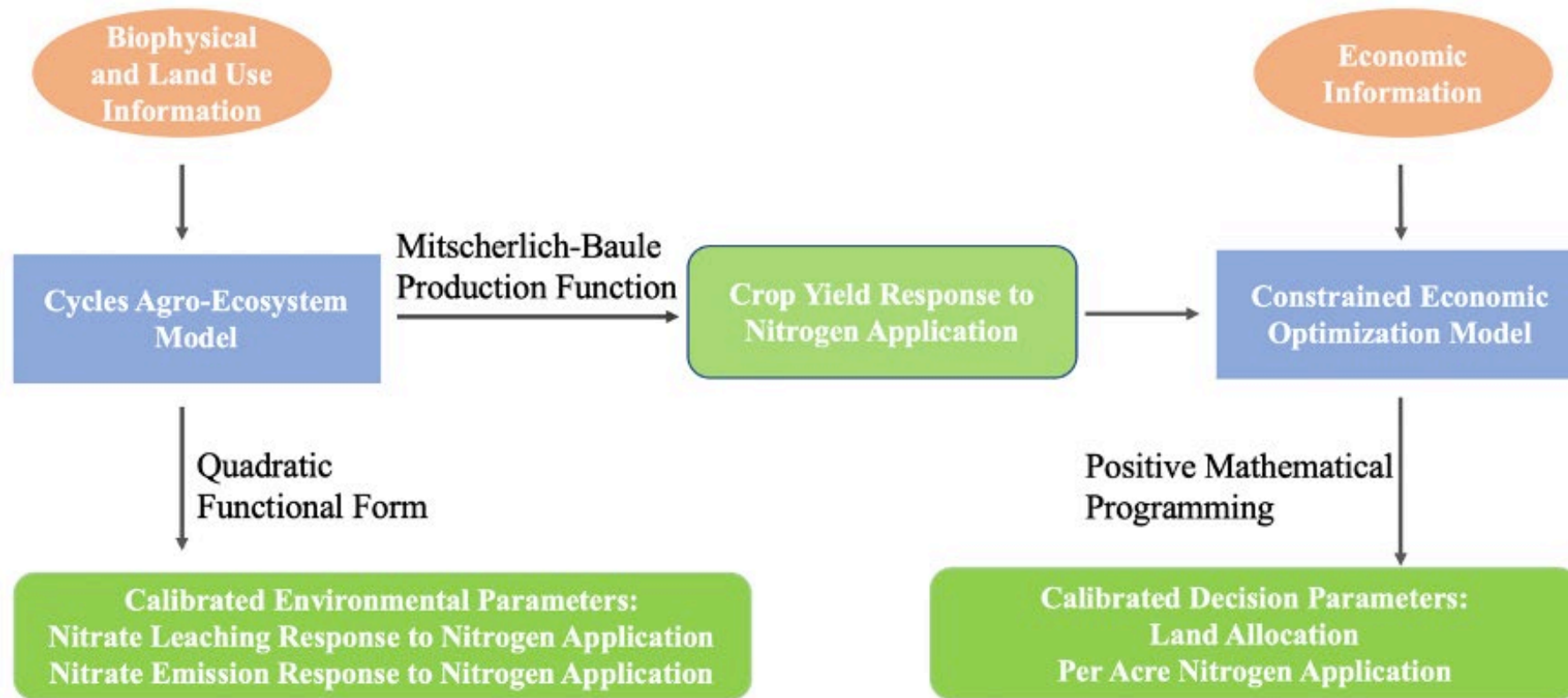
Policy Scenarios

- Command-and-control Water Policies (mimic TMDL)
 - Target reductions in nitrate leaching to the lake
 - Impose 5% to 95% leaching reduction caps relative to the status quo
 - Land owners could adjust both land use allocation and nitrogen fertilizer application to fulfil the requirements

Results

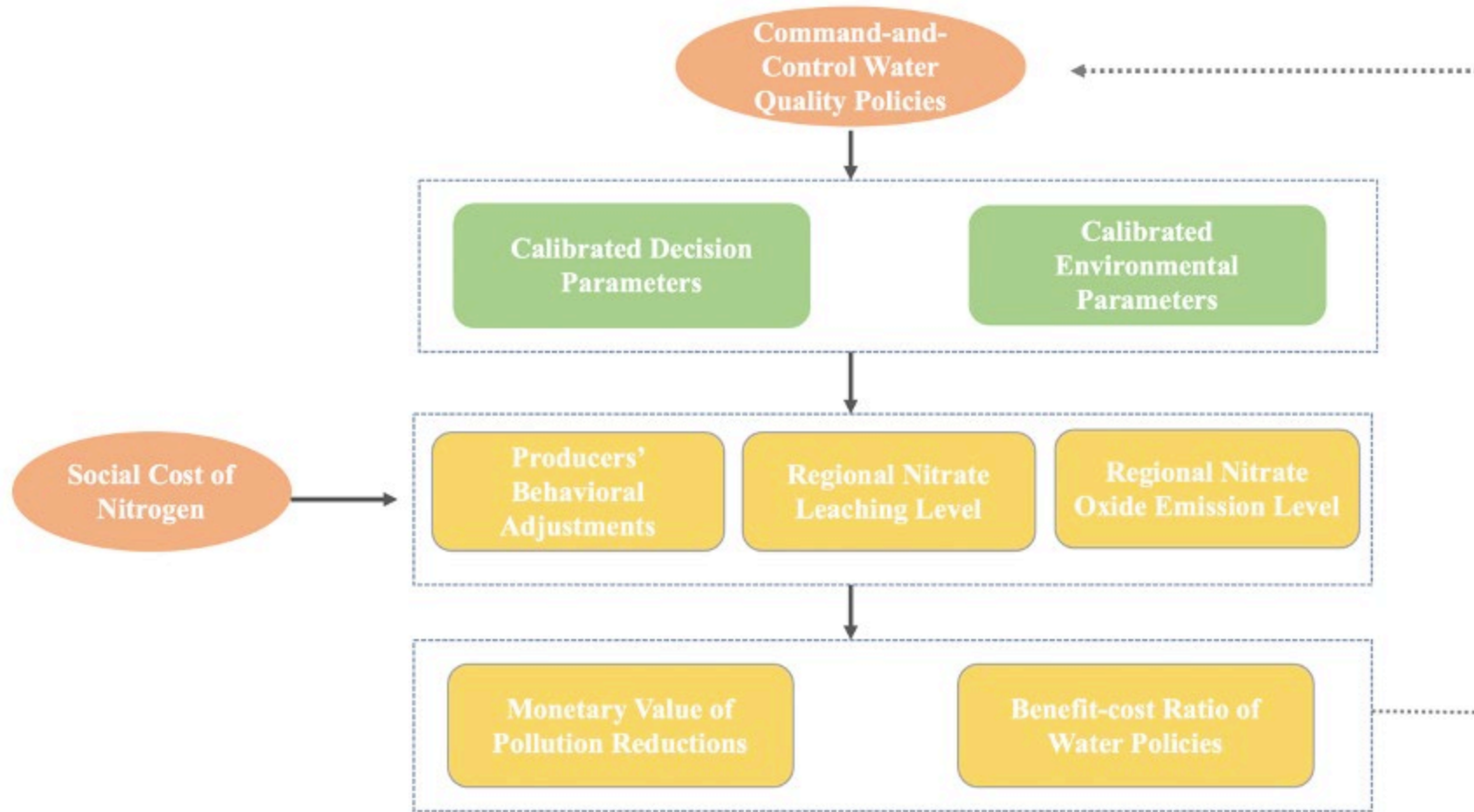
- In the application to an agricultural-dominated watershed with a long history of water-quality degradation, we find:
 - Nitrous oxide emissions decline in proportion to changes in nitrate leaching:
 - 10% reduction in nitrate leaching is associated with a 12% reduction in nitrate oxide emissions
 - The co-benefits from nitrous oxide abatement are highly variable across years because of interannual variation in relative crop prices and weather
 - Variation in relative crop prices affects the behavioral adjustments made by farmers to meet water quality targets; variation in weather, particularly in the timing and amount of precipitation, affects the relationship between farmer decision making and the joint production of leaching and emissions
 - Across years, accounting for the co-benefits would increase the benefit-cost ratio, and in some circumstances even change the results of benefit-cost analysis

Modeling Framework



(a) Calibration Process

Modeling Framework

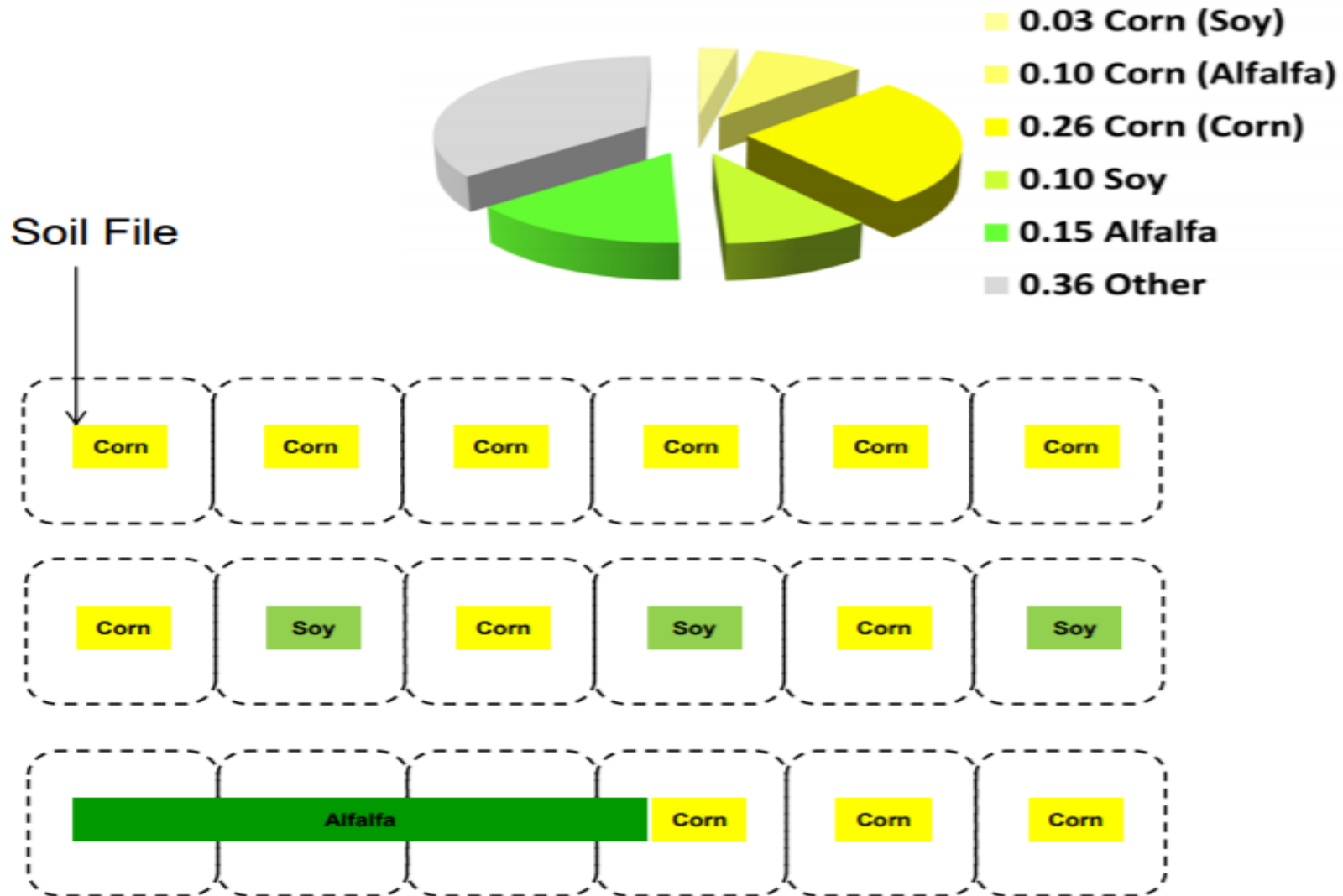


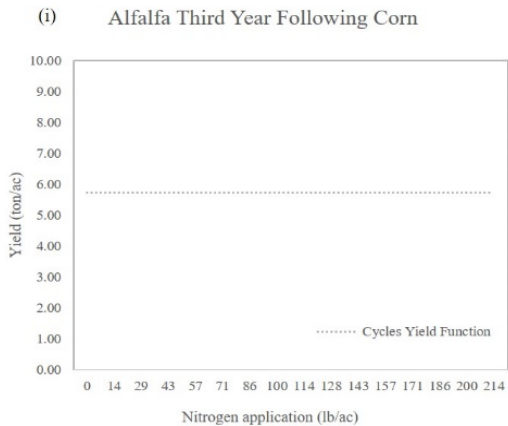
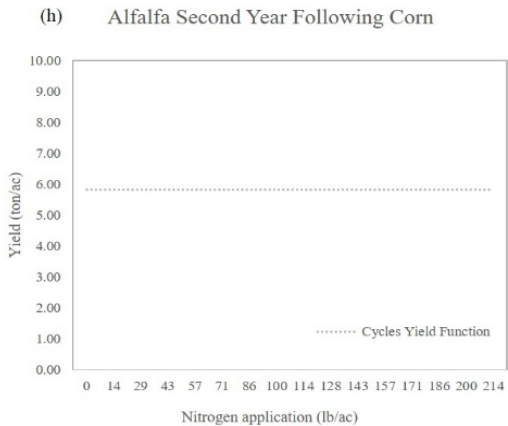
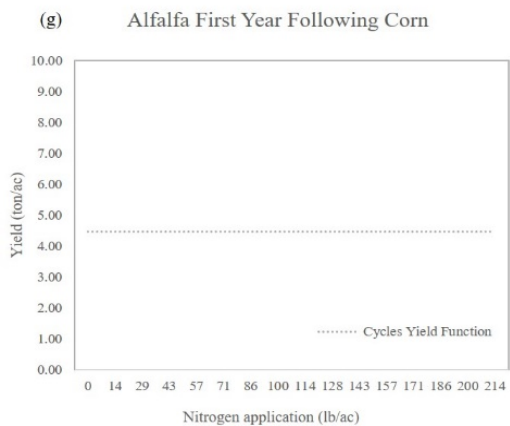
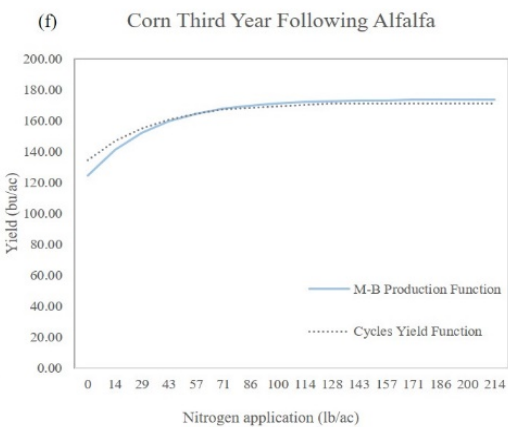
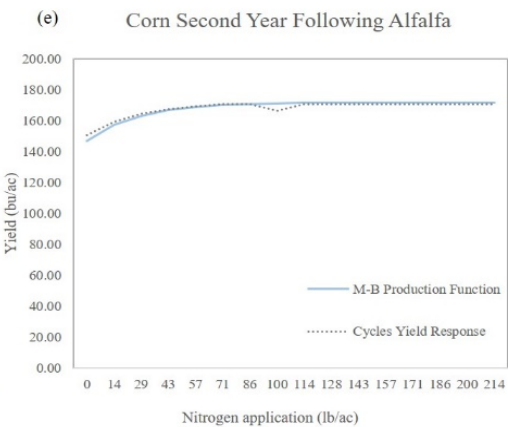
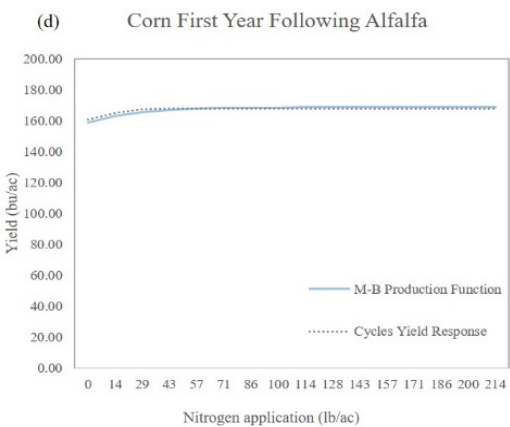
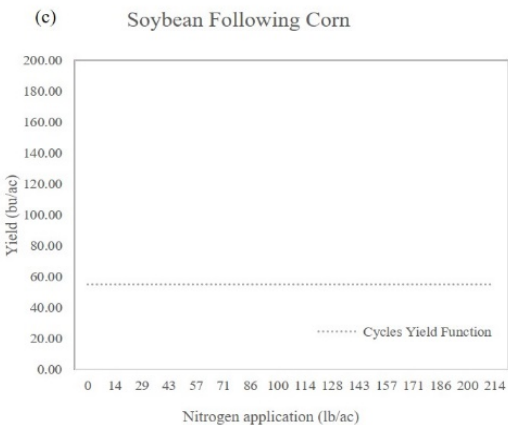
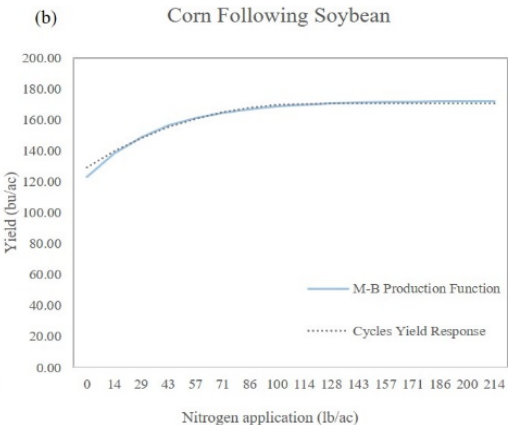
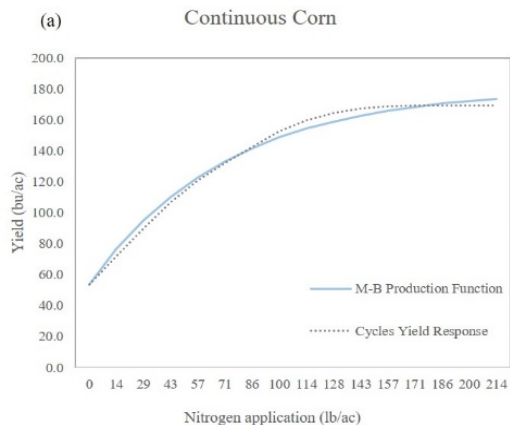
(b) Policy Simulation Process

Cycles Agro-Ecosystem Model

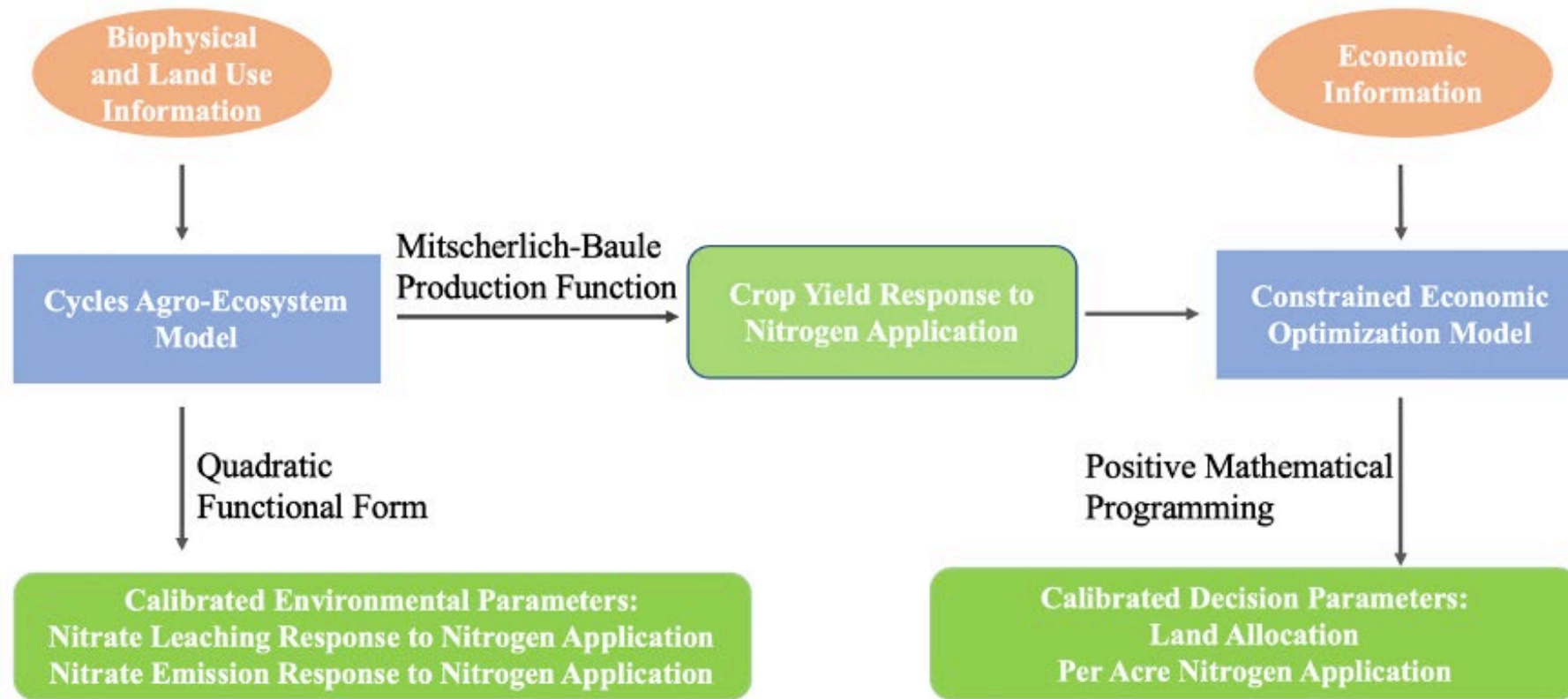
- Multi-crop, multi-year, process-based model of crop production and the water, carbon, and nitrogen cycles
- Input:
 - Daily weather (minimum and maximum temperature, precipitation, solar radiation, dew point and wind speed)
 - Soil description (layer thickness, clay, sand and organic matter content)
 - Cropping sequence
 - Management information
- Output:
 - Crop yield response to nitrogen application
 - Nitrate leaching response to nitrogen application
 - Nitrous Oxide emission response to nitrogen application

Crop Rotations





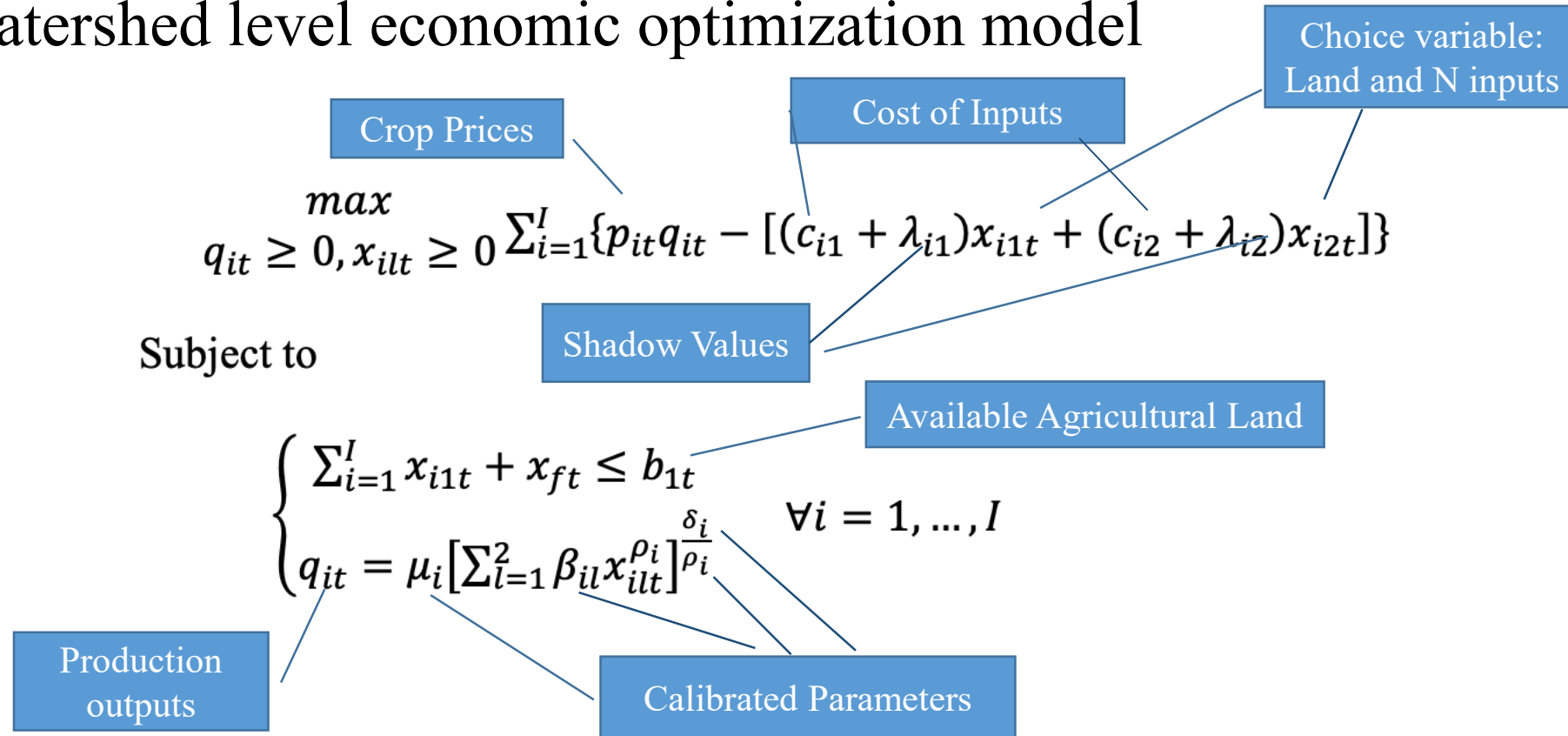
Modeling Framework



(a) Calibration Process

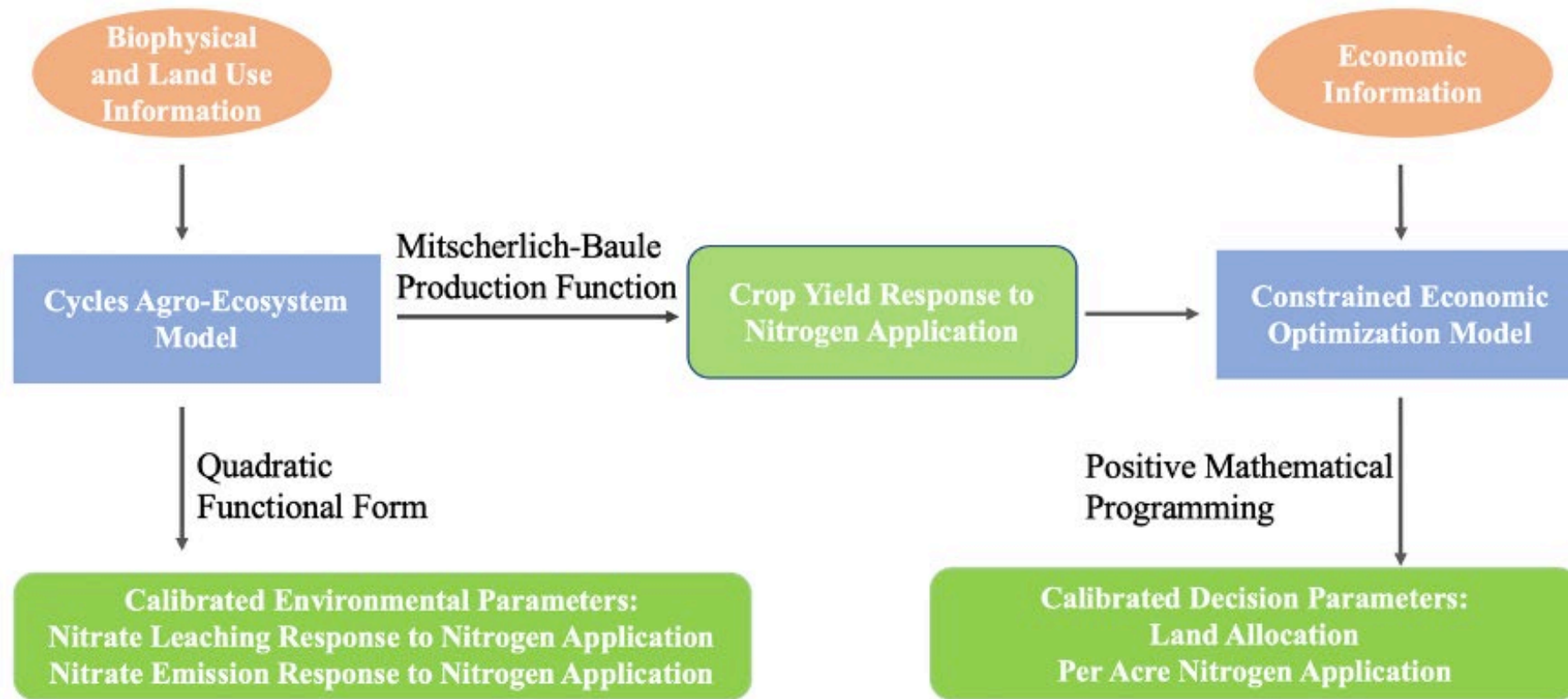
Constrained Economic Optimization Model

- A watershed level economic optimization model



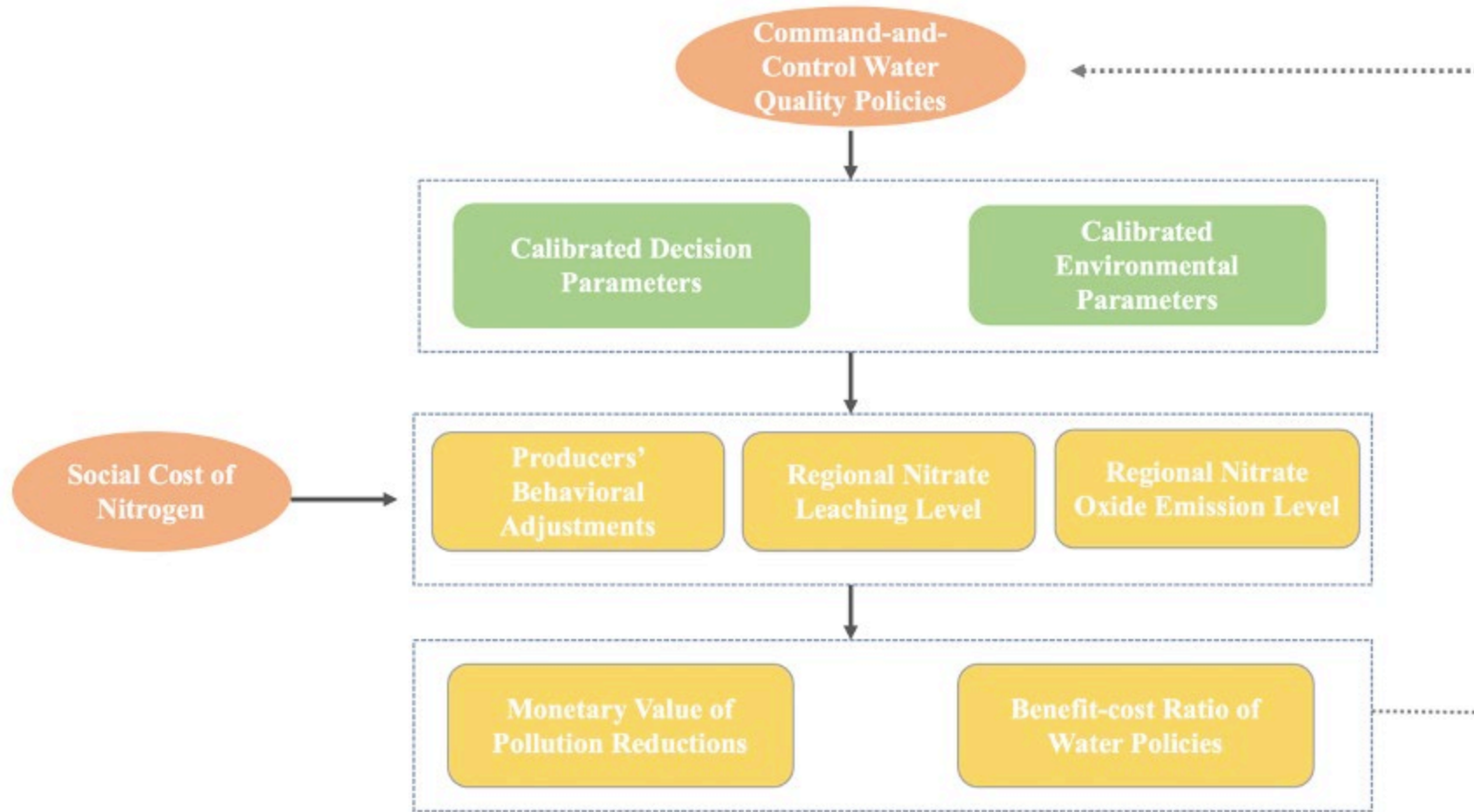
- Calibrate the parameters against observed supply elasticities and followed the calibration procedure of Merel et al. (2011) and Merel et al. (2013)

Modeling Framework



(a) Calibration Process

Modeling Framework



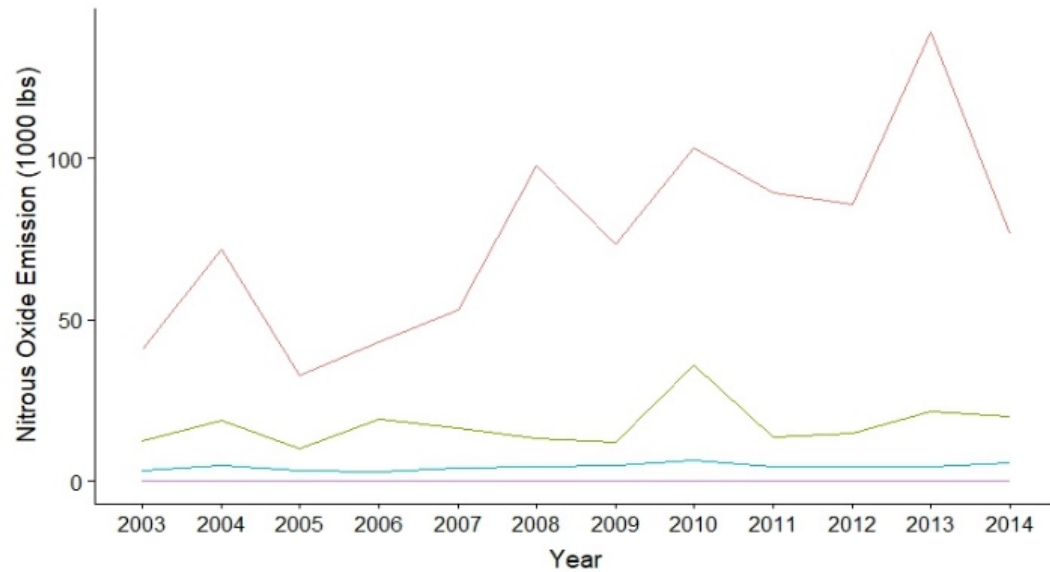
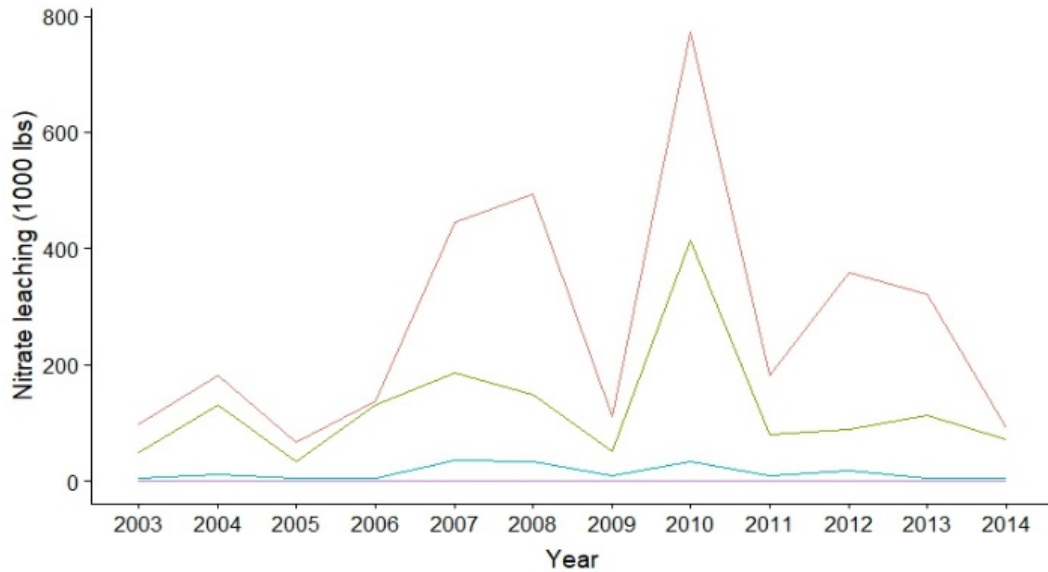
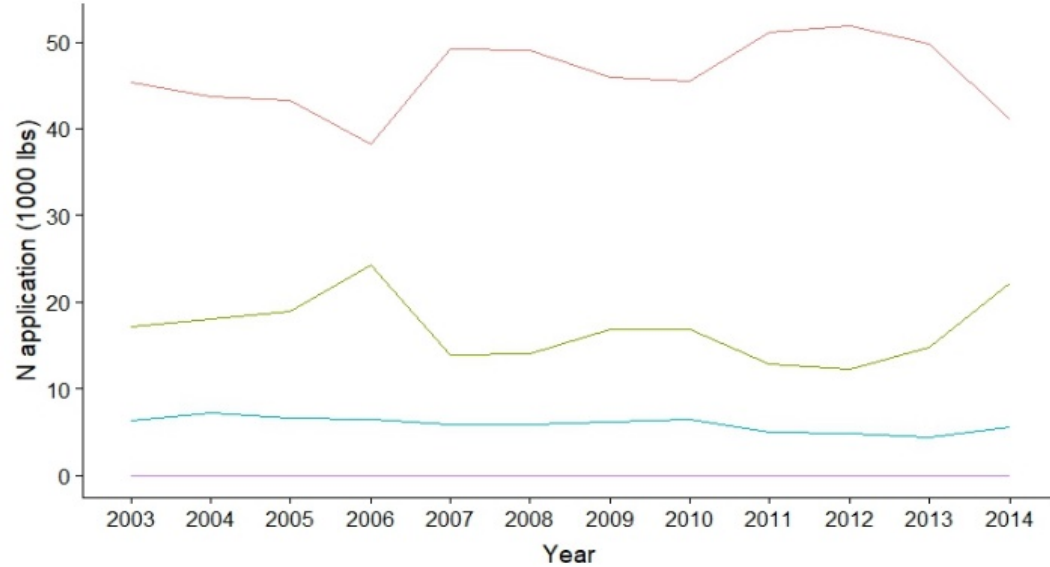
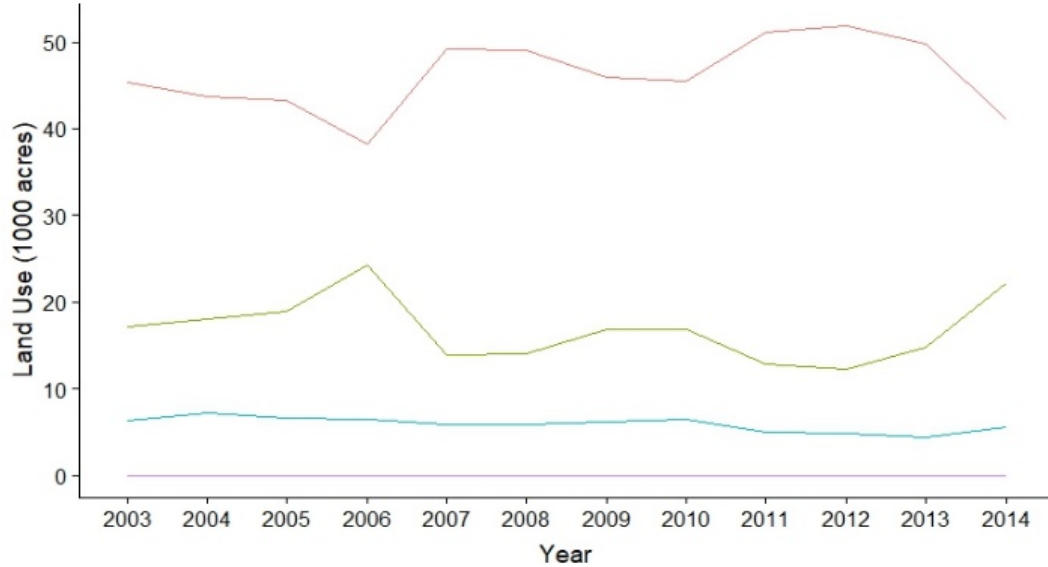
(b) Policy Simulation Process

Monetary Value and Benefit-Cost Analysis

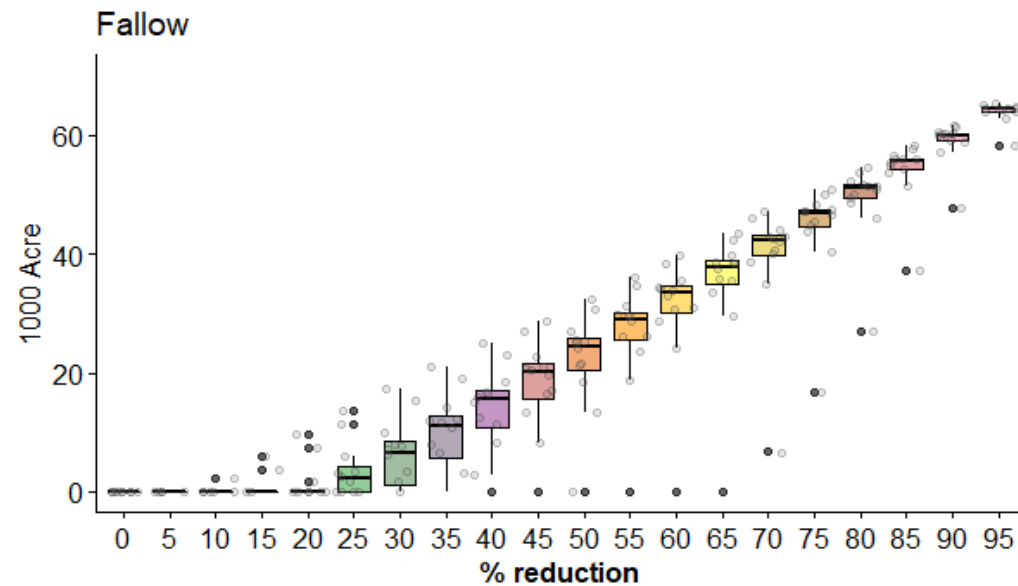
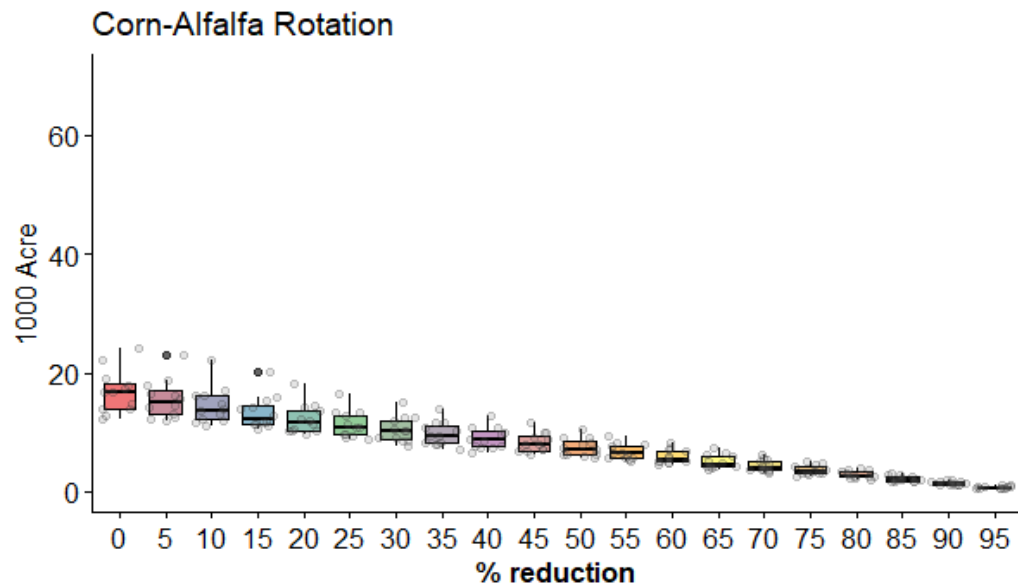
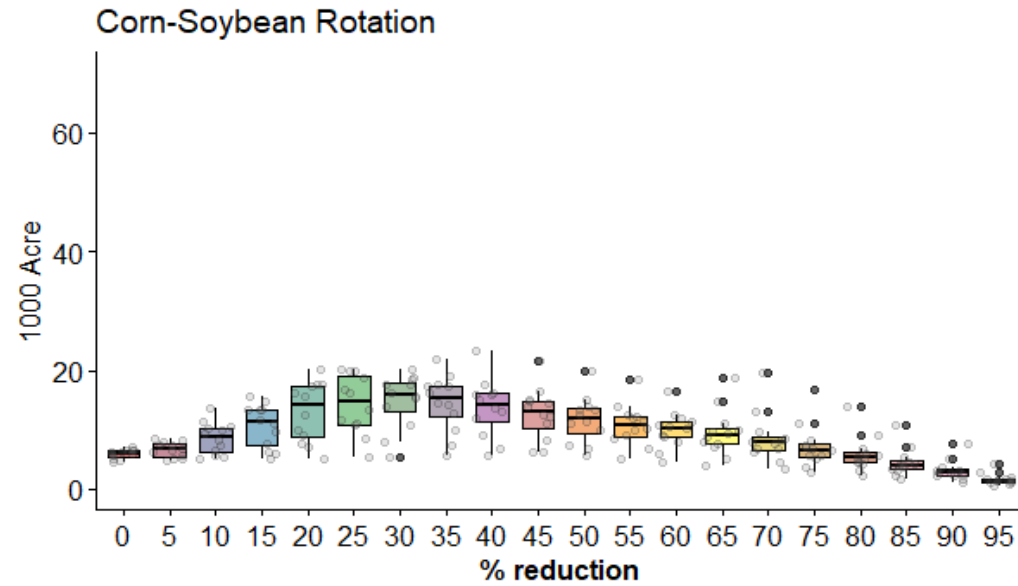
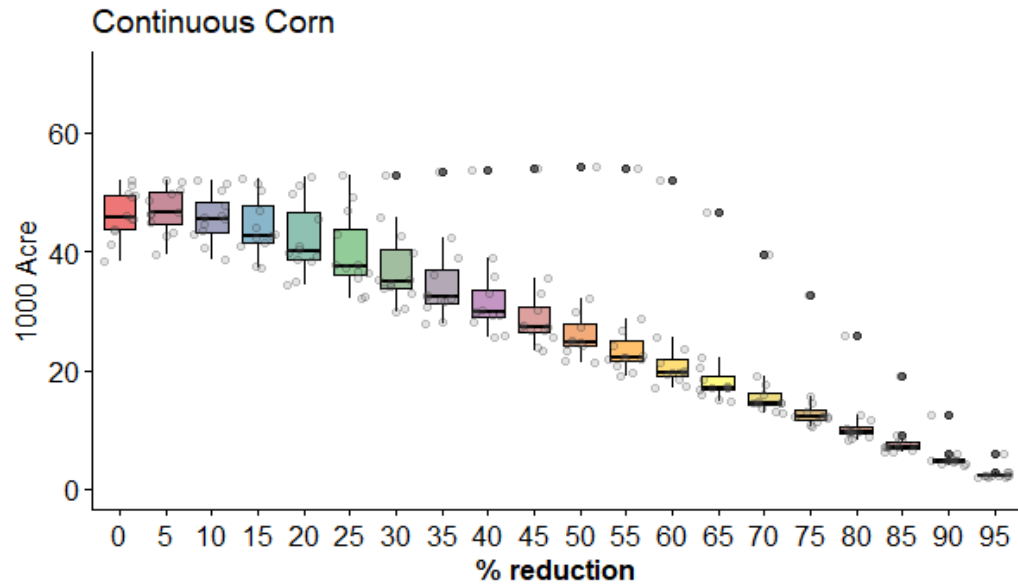
- Back-of-the-envelope calculation
- Benefits: monetary value of nitrogen leaching and nitrogen emission reductions in terms of social costs
 - Value of social costs come from Keeler et al. 2016
 - Average Value per Kg N
 - NO_3^- : \$0.01
 - N_2O : \$0.22
- Costs: reduction in agricultural profits

Status Quo Results

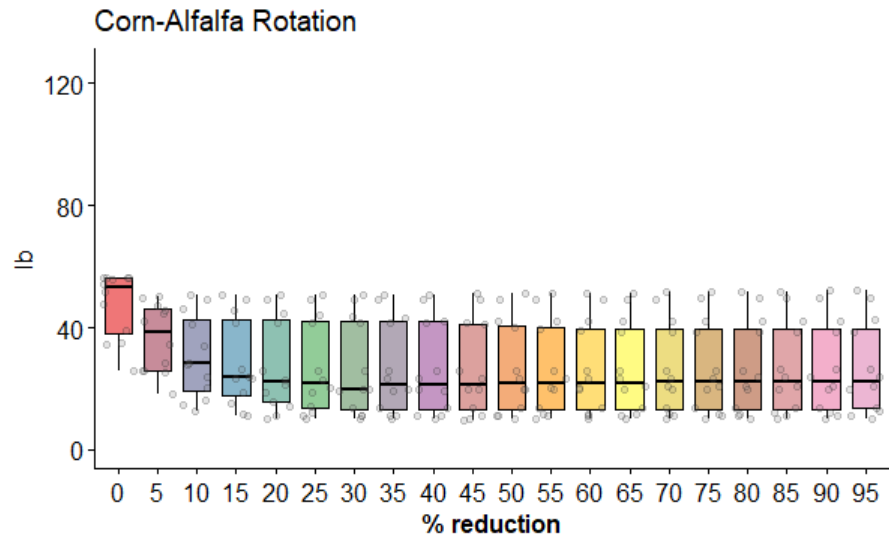
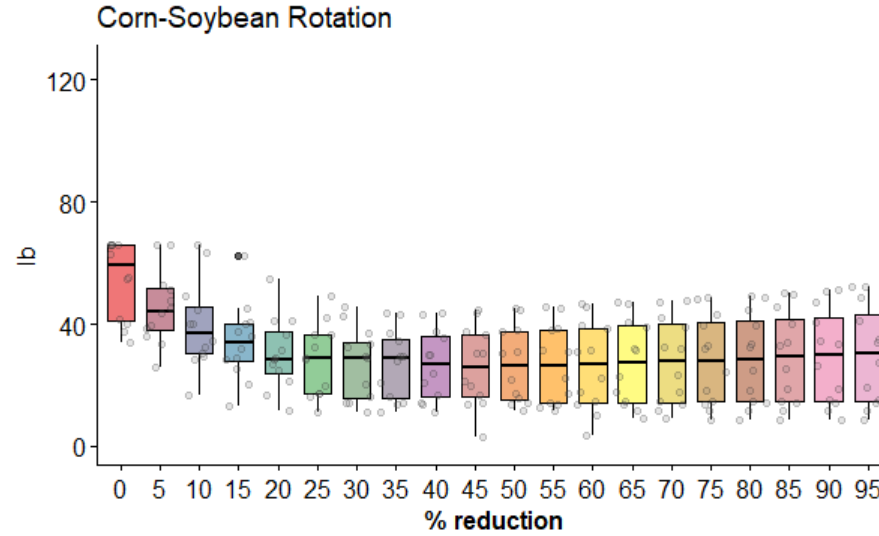
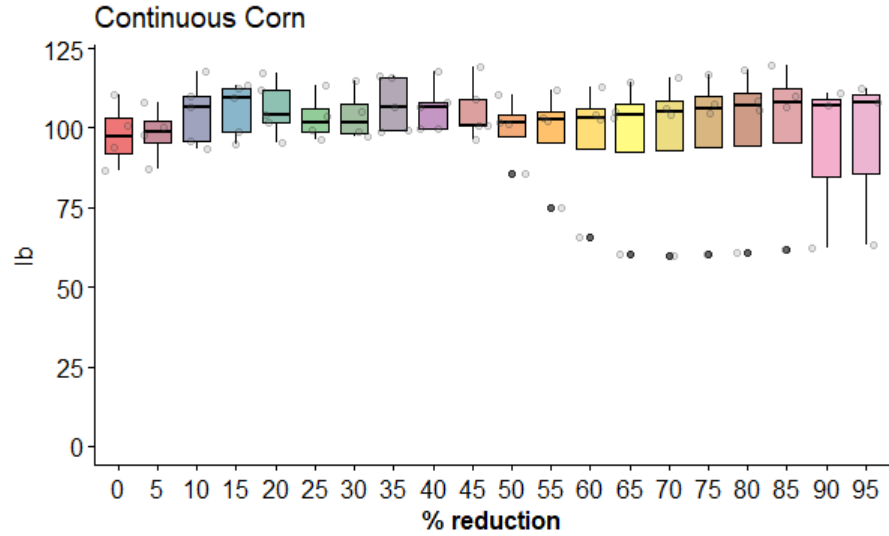
Crop Rotation — Continuous Corn — Corn-Alfalfa Rotation — Corn-Soybean Rotation — Fallow



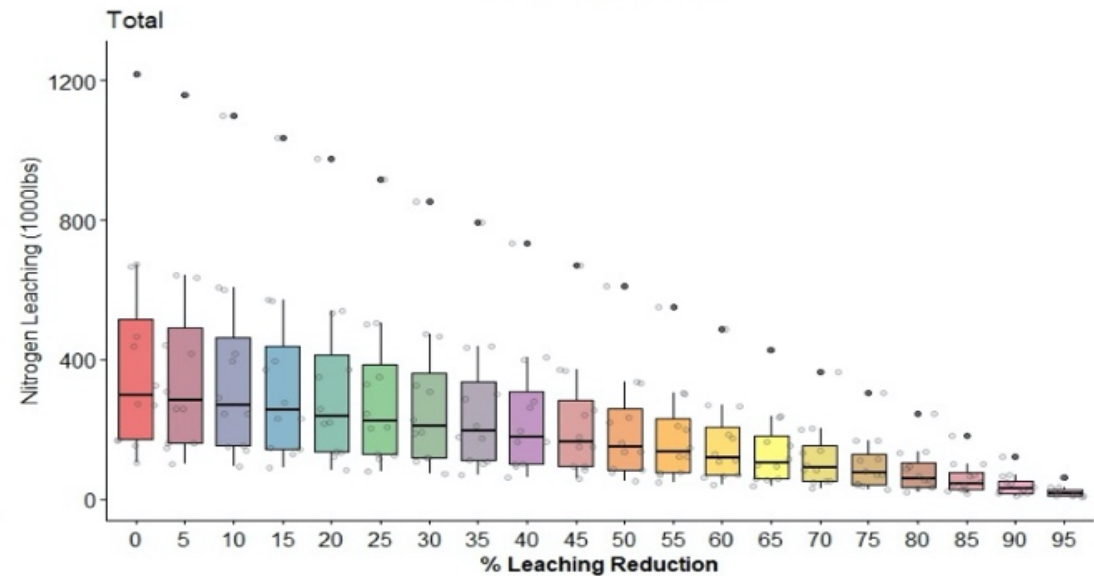
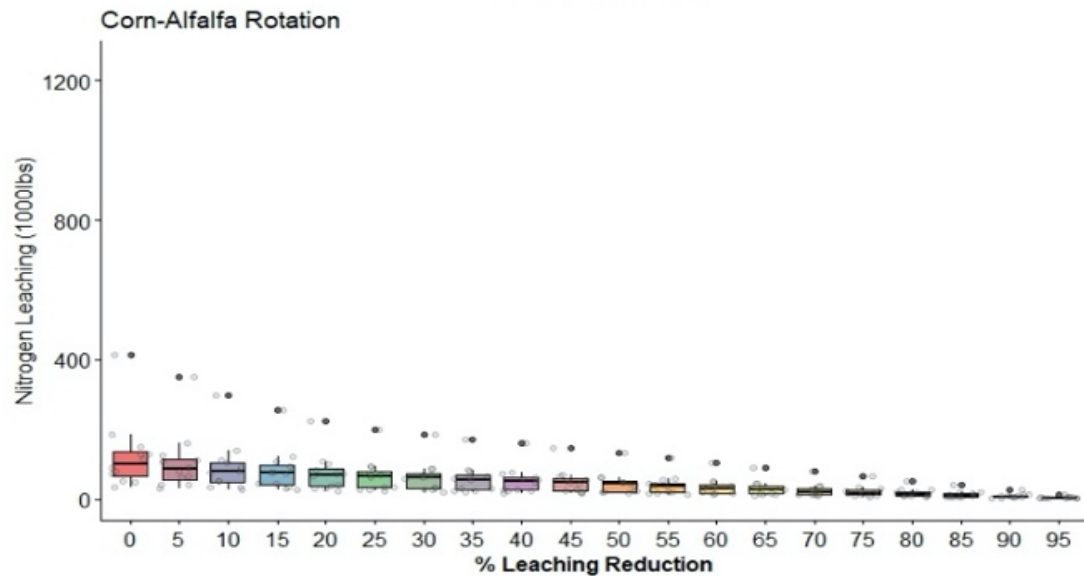
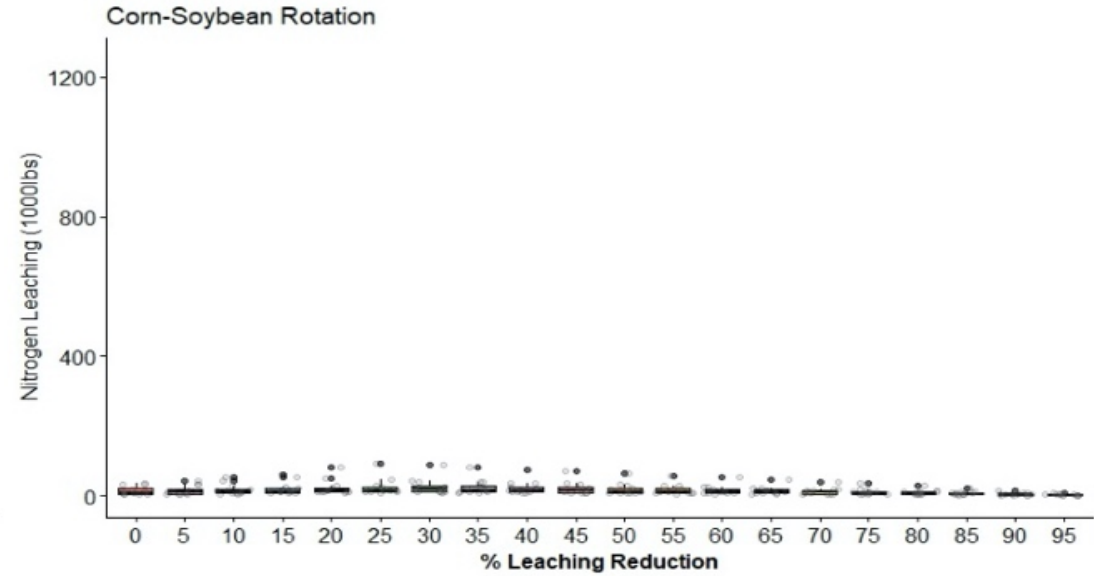
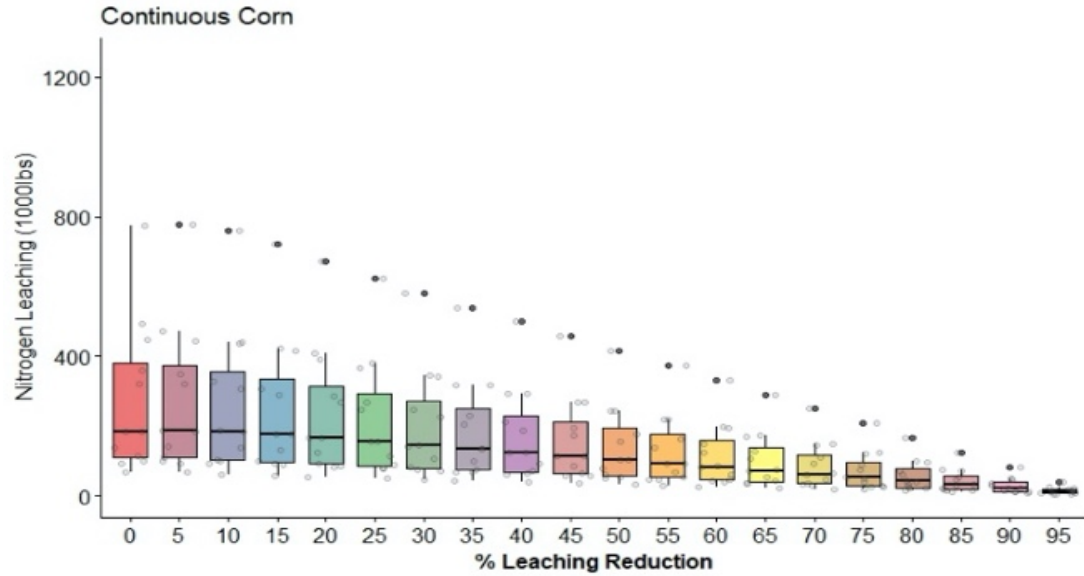
Behavioral Adjustments (Land Allocation)



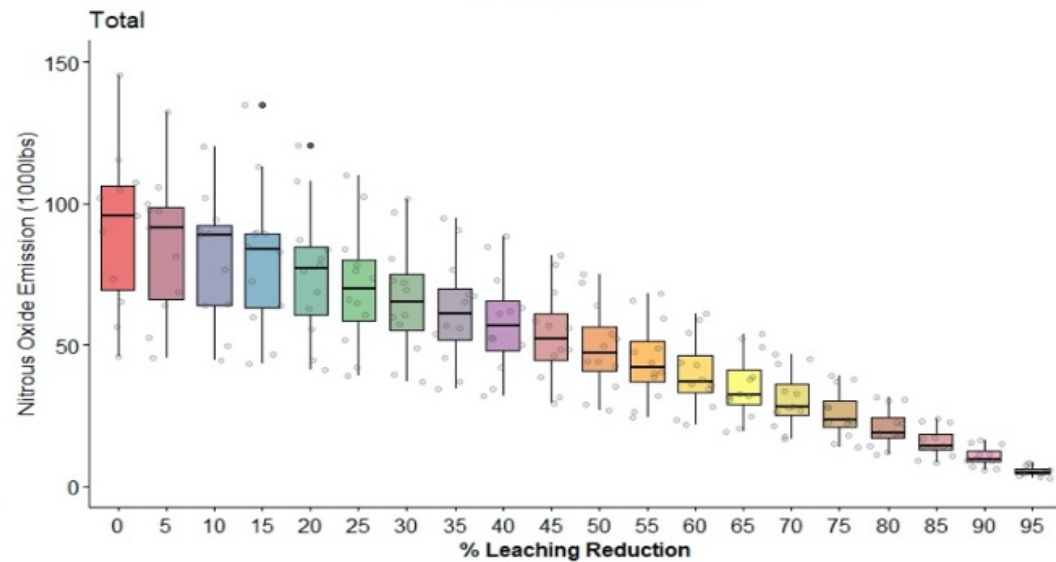
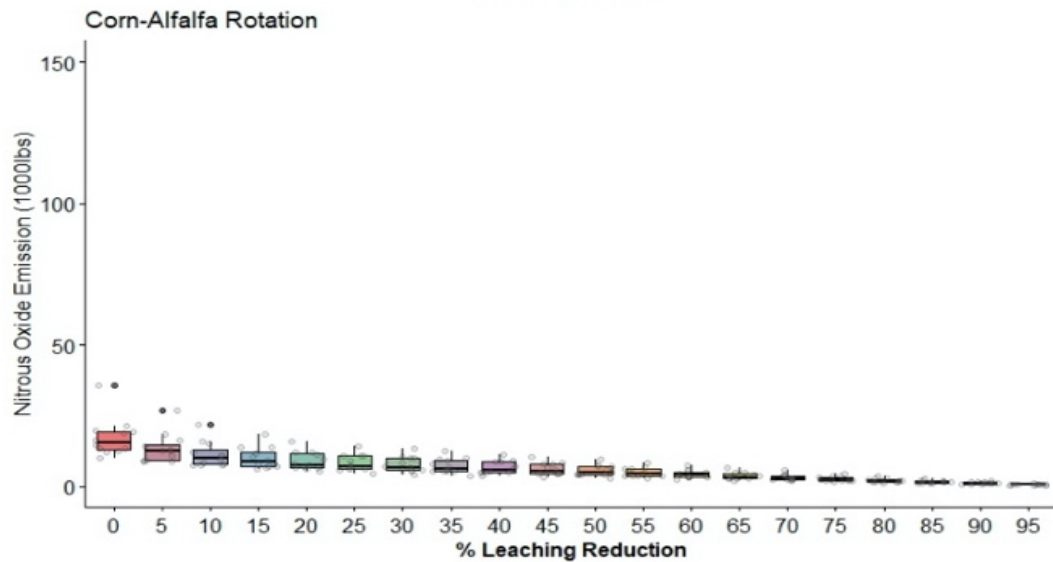
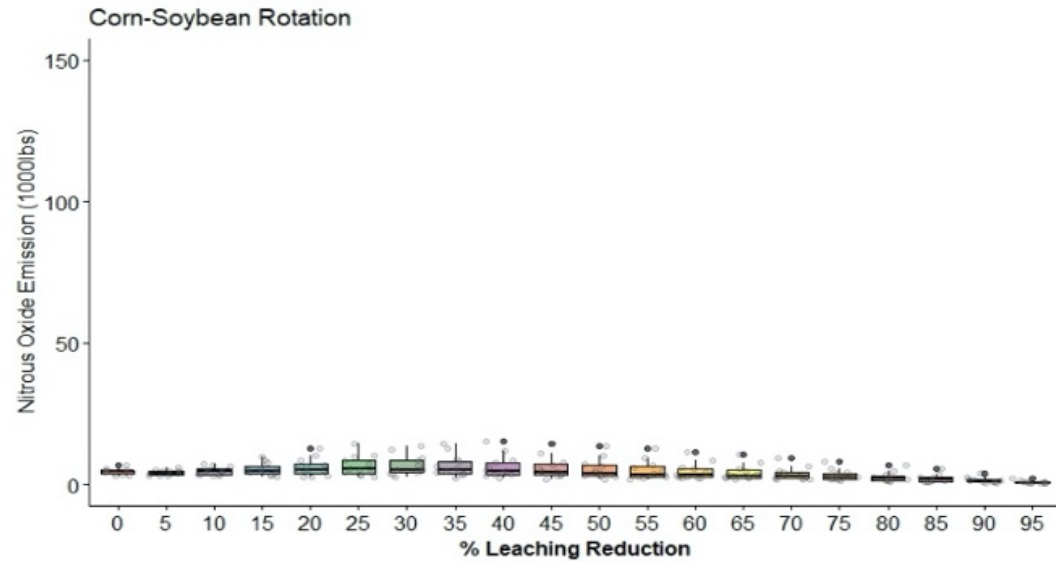
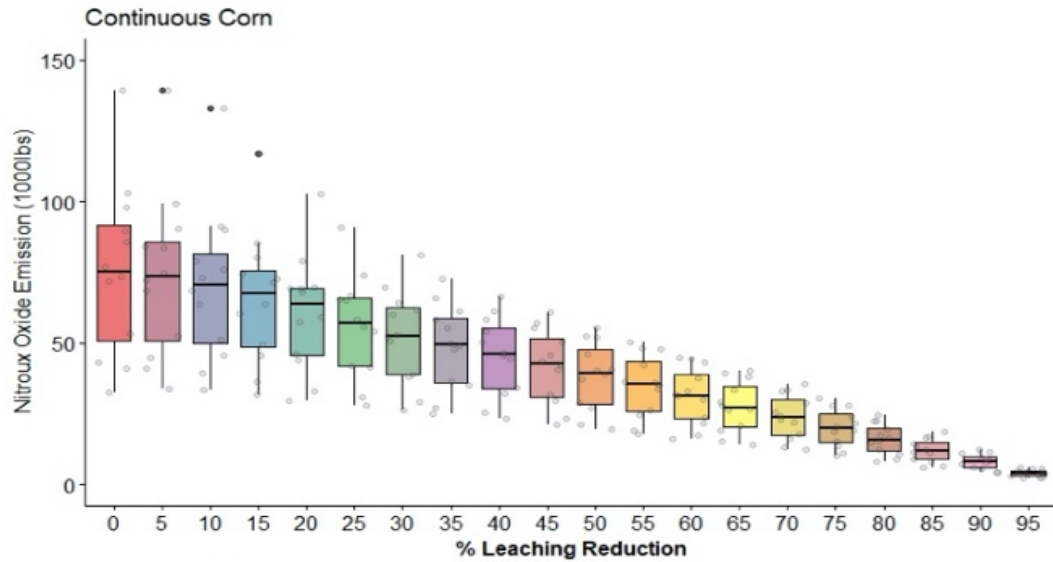
Behavioral Adjustments (Nitrogen Application)



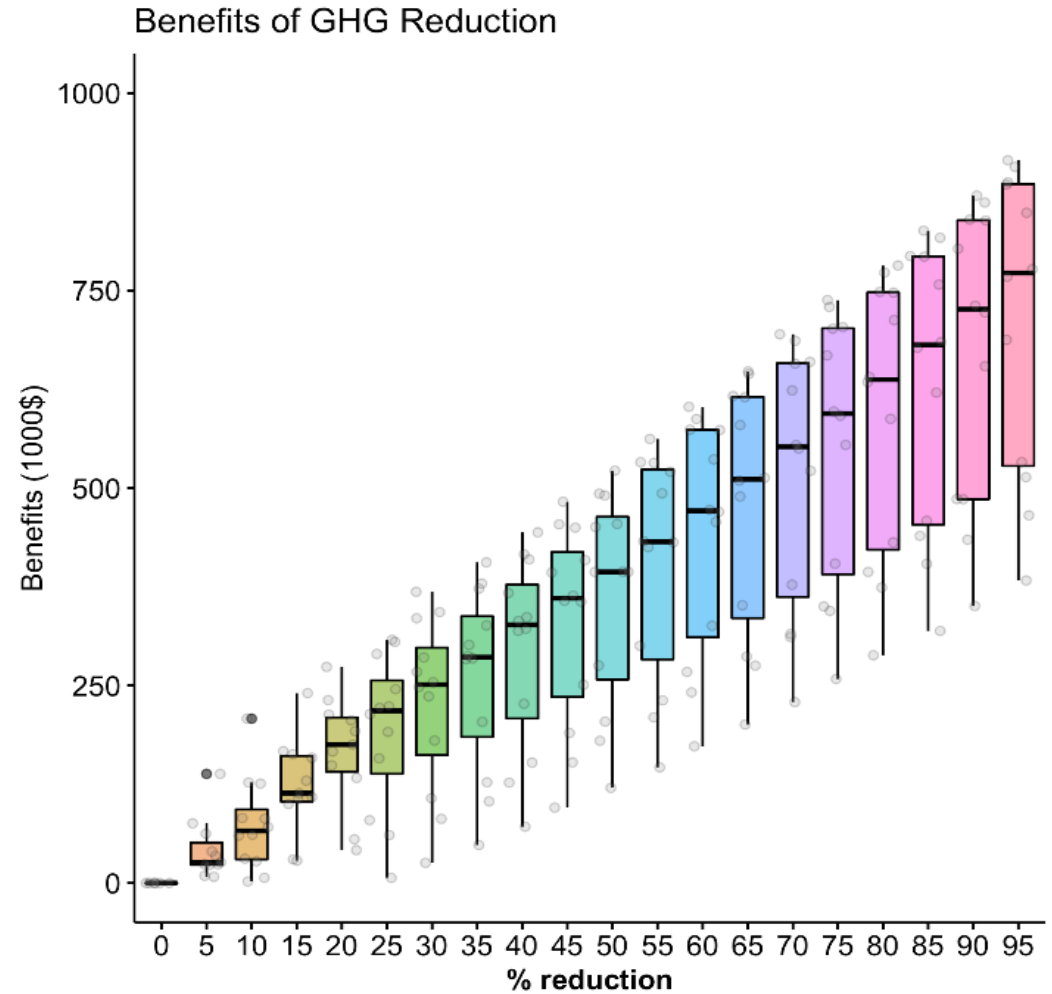
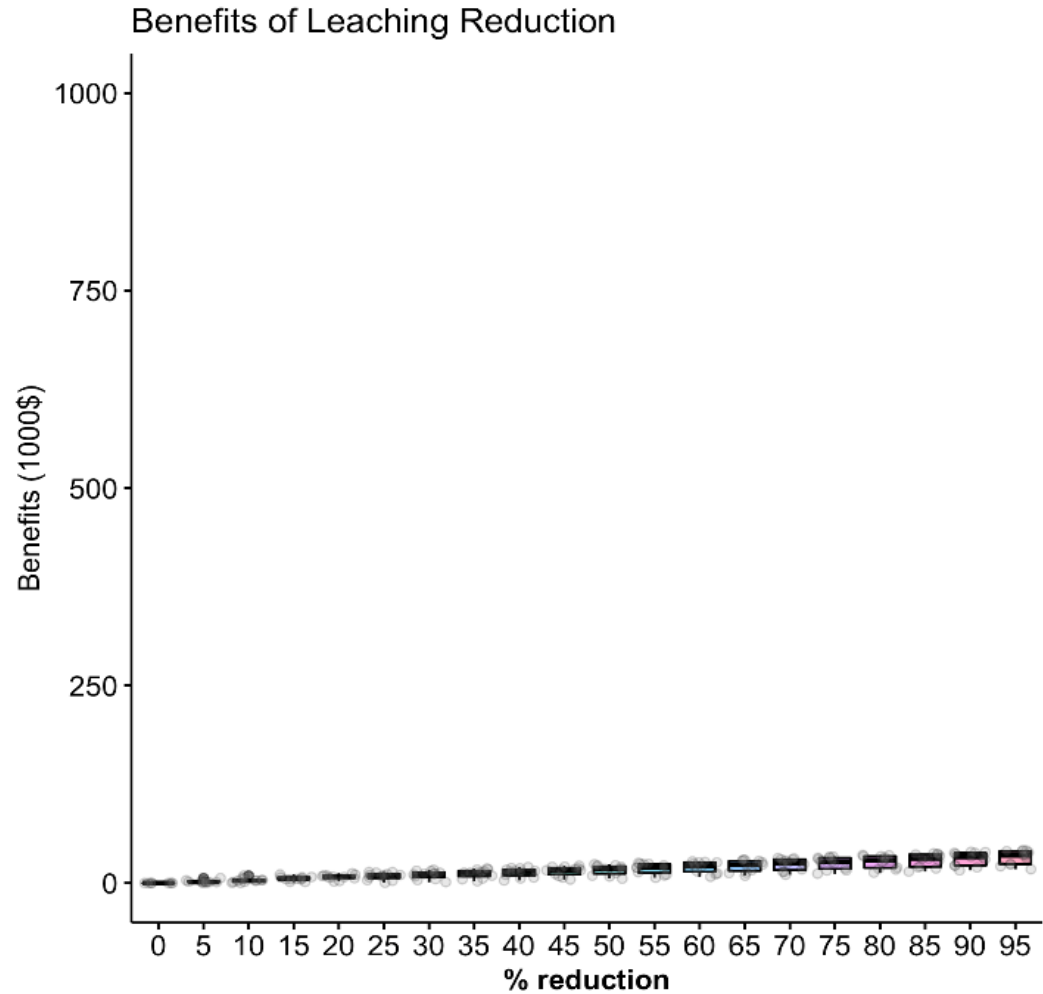
Pollution Levels (Nitrate Leaching)



Pollution Levels (Nitrous Oxide Emissions)



Monetary Benefits



Quantification of Co-Benefits

Leaching cap (% reduction)	Reduction (1000 lbs)		Benefits (\$1000)		Cost (\$m.)	Benefit-cost ratio	
	Leaching	Emissions	Leaching	Emissions		w/out co-benefits	w/ co-benefits
5	20.5	5.5	1.8	38.6	-1.469	-0.001	-0.027
10	41.1	12.1	3.4	73.6	-1.302	-0.003	-0.06
15	61.6	17.2	5.1	111.7	-1.010	-0.005	-0.12
20	82.2	22.0	7.0	152.9	-0.614	-0.01	-0.26
25	102.7	25.9	8.7	192.0	-0.111	-0.078	-1.80
30	123.2	28.6	10.4	227.7	0.483	0.02	0.49
35	143.8	33.4	11.8	260.2	1.145	0.01	0.24
40	164.3	37.4	13.4	293.7	1.866	0.007	0.17
45	184.9	41.3	15.0	329.5	2.648	0.006	0.13
50	205.4	45.6	16.6	364.4	3.502	0.005	0.11
55	225.9	49.9	18.3	401.4	4.447	0.004	0.09
60	246.5	54.1	20.0	440.0	5.510	0.004	0.08
65	267.0	59.0	21.7	477.4	6.724	0.003	0.06
70	287.5	63.3	23.4	515.1	8.112	0.003	0.07
75	308.1	67.8	25.2	553.4	9.692	0.003	0.06
80	328.6	72.3	27.0	592.6	11.528	0.002	0.05
85	349.2	76.8	28.8	632.6	13.740	0.002	0.05
90	369.7	81.5	30.6	673.1	16.563	0.002	0.04
95	390.2	88.8	32.5	714.0	20.646	0.002	0.04

In year 2009,
benefit-cost
ratio > 1

In year 2004,
benefit-cost
ratio > 1

Summary

- GHG emission reductions correspond proportionately with changes in leaching
 - 10% reduction in leaching → 12% reduction in emissions
 - Fertilizer adjustments along intensive margin
 - Choice of rotation and fallow along extensive margin
- Co-benefits highly variable across years
 - Precipitation (affect relationship between fertilizer use and leaching)
 - Relative crop prices (affect behavioral adjustments by land owners to reduce nitrate leaching)

Summary

- Quantifying co-benefits is important in designing water quality policies
 - The benefit-cost ratio would increase
 - Could potentially change the results of cost-benefit analysis
 - The magnitude of the co-benefits depends on the stringency of the water quality instrument
- Neglecting co-benefits when making decisions about water policy could lead to socially inefficient outcomes
 - Under-regulation of fertilizer use
 - Farmers lack an incentive to participate in voluntary environmental programs

Contributions to the Literature

- We demonstrate the advantages of using an integrated assessment model in support of benefit-cost analyses of water policies.
 - Our framework supports the quantification of multiple environmental benefits arising from a single policy instrument, which has rarely been quantified in the literature on water quality.
- We provide evidence of the importance of understanding the co-benefits associated with water policies.
- We highlight the importance of understanding factors that drive heterogeneity in co-benefits.
 - It is crucial to account for these behavioral adjustments when designing effective and efficient environmental policy.



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