In Search of Spatial Opportunities for Sustainable Bioenergy Production

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(http://www.esd.ornl.gov/~zij/)

CBES Presentation
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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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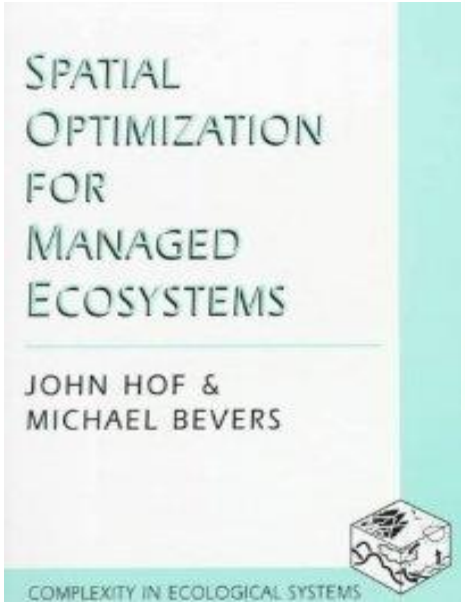
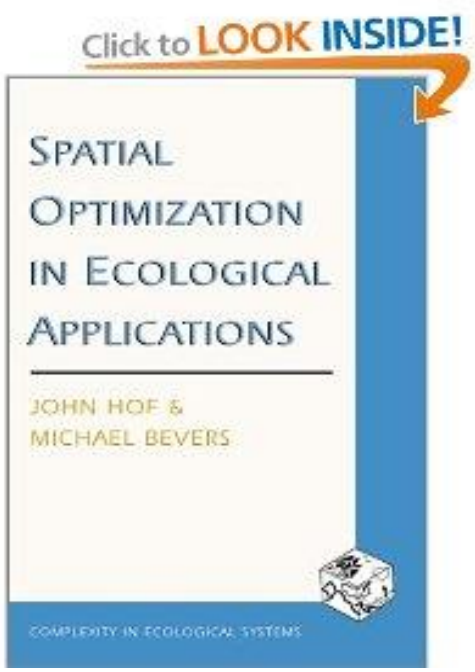
Nearly every important resource management question is a spatial optimization problem.





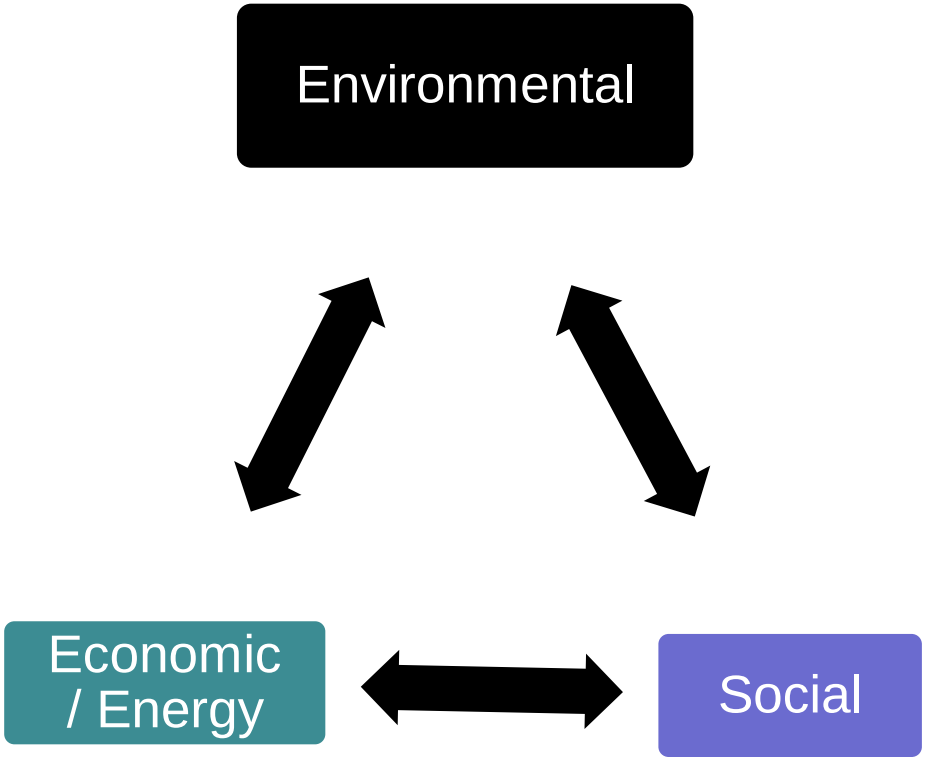
Decision variables are spatial: Spatial allocation of crops and/or management actions on landscape.

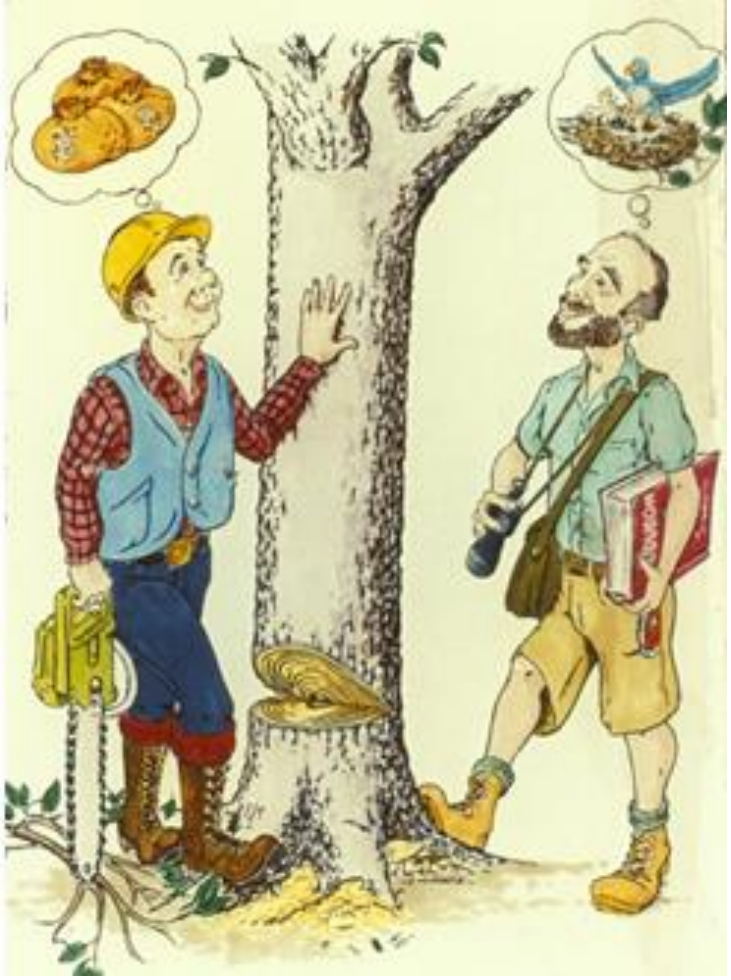
1	1	2	2
1	1	1	2
1	1	3	2
1	1	3	3
3	3	3	3

Sustainability indicators

OBJECTIVES

Sustainable?

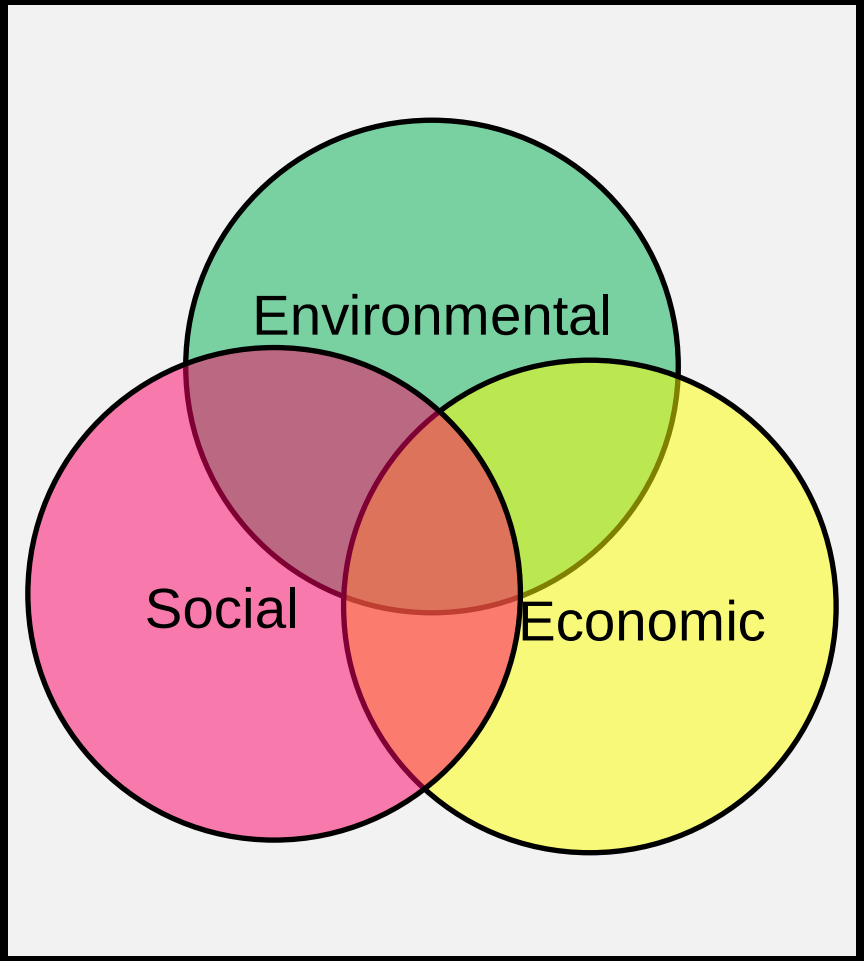


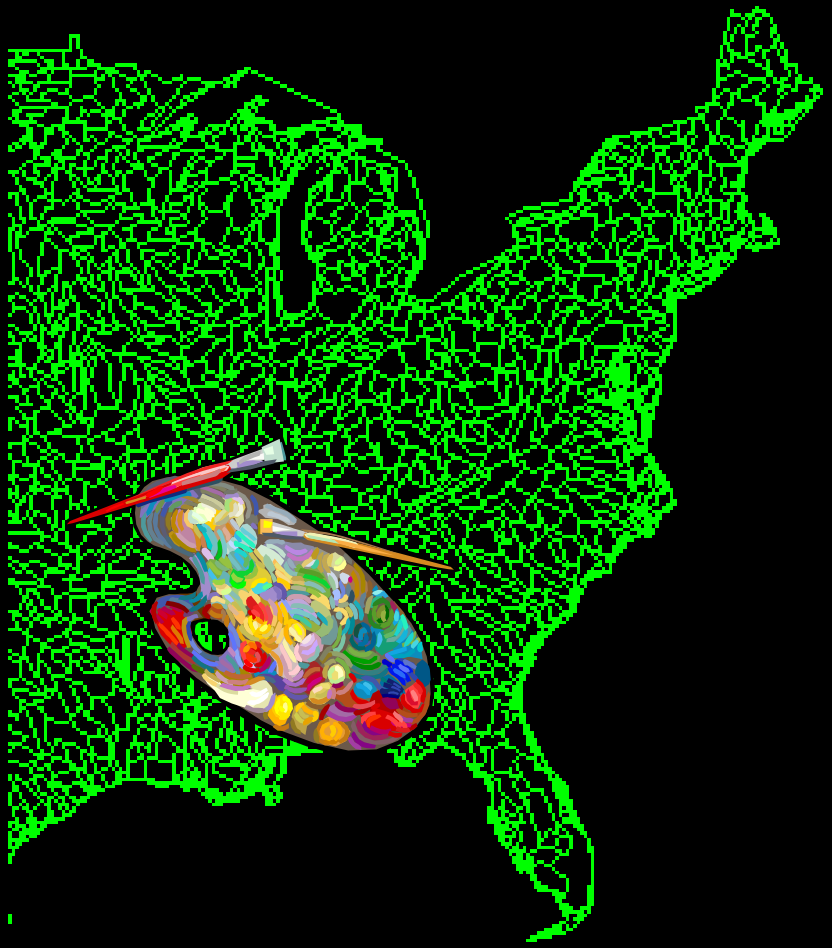


Source: V. Dale

Environmental
CBES
Center for BioEnergy Sustainability
Economic
Social

Where do they intersect?





Color US bioenergy sustainability

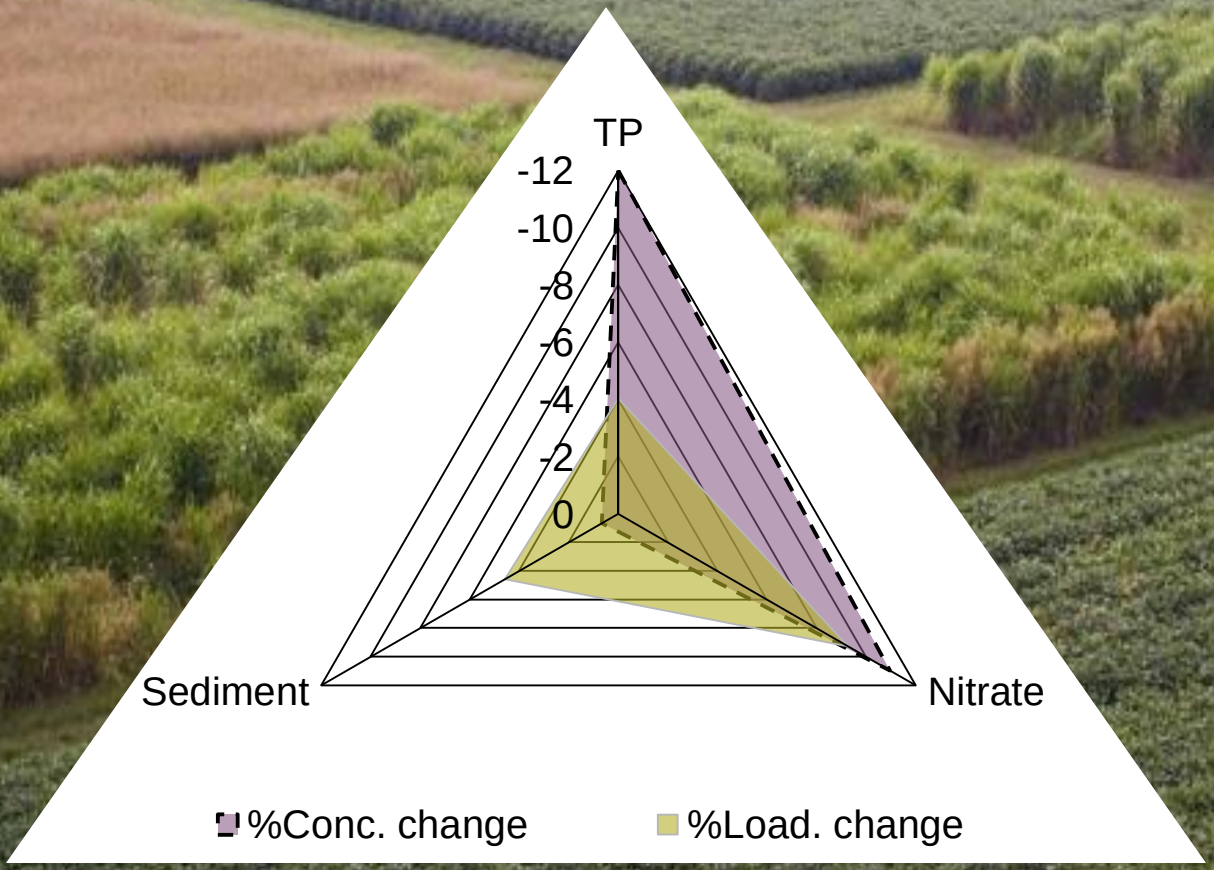
Sustainability indicators

McBride et al. (2011) *Ecological Indicators* 11:1277-1289

Environment	Indicator	Units
Soil quality	1. Total organic carbon (TOC)	Mg/ha
	2. Total nitrogen (N)	Mg/ha
	3. Extractable phosphorus (P)	Mg/ha
	4. Bulk density	g/cm^3
Water quality and quantity	5. Nitrate concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	6. Total phosphorus (P) concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	7. Suspended sediment concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	8. Herbicide concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	9. storm flow	L/s
	10. Minimum base flow	L/s
	11. Consumptive water use (incorporates base flow)	feedstock production: m^3/ha/day; biorefinery: m^3/day

Environment	Indicator	Units
Greenhouse gases	12. CO_2 equivalent emissions (CO_2 and N_2O)	kgC_{eq}/GJ
Biodiversity	13. Presence of taxa of special concern	Presence
	14. Habitat area of taxa of special concern	ha
Air quality	15. Tropospheric ozone	ppb
	16. Carbon monoxide	ppm
	17. Total particulate matter less than 2.5µm diameter ($PM_{2.5}$)	$\mu g/m^3$
	18. Total particulate matter less than 10µm diameter (PM_{10})	$\mu g/m^3$
Productivity	19. Aboveground net primary productivity (ANPP) / Yield	gC/m^2/year

Sustainability indicators for water quality (2030 – baseline)



Spatial allocation

DECISION VARIABLES

Two approaches

Land sparing	Land sharing
Intensively managed dedicated energy crops offset by conservation of other lands.	Designed bioenergy landscapes with both residue or harvest for bioenergy and features to support ecosystem services.
Genetic yield improvement promising: • palm oil (southeast asia) • soybean, rapeseed, sunflower • sugar cane	Less potential for yield increases
Incentives exist • Conservation Reserve Program	Incentives are lacking • riparian buffers, perennial • wetlands or farm ponds • woodland edges, pollinators
Concerns: • GMO's • Increased fertilizer, pesticide, water use => lower environ. sustainability.	Concerns: • Creation of ecological traps • Logistic challenges of working around wildlife-friendly elements

Intensification

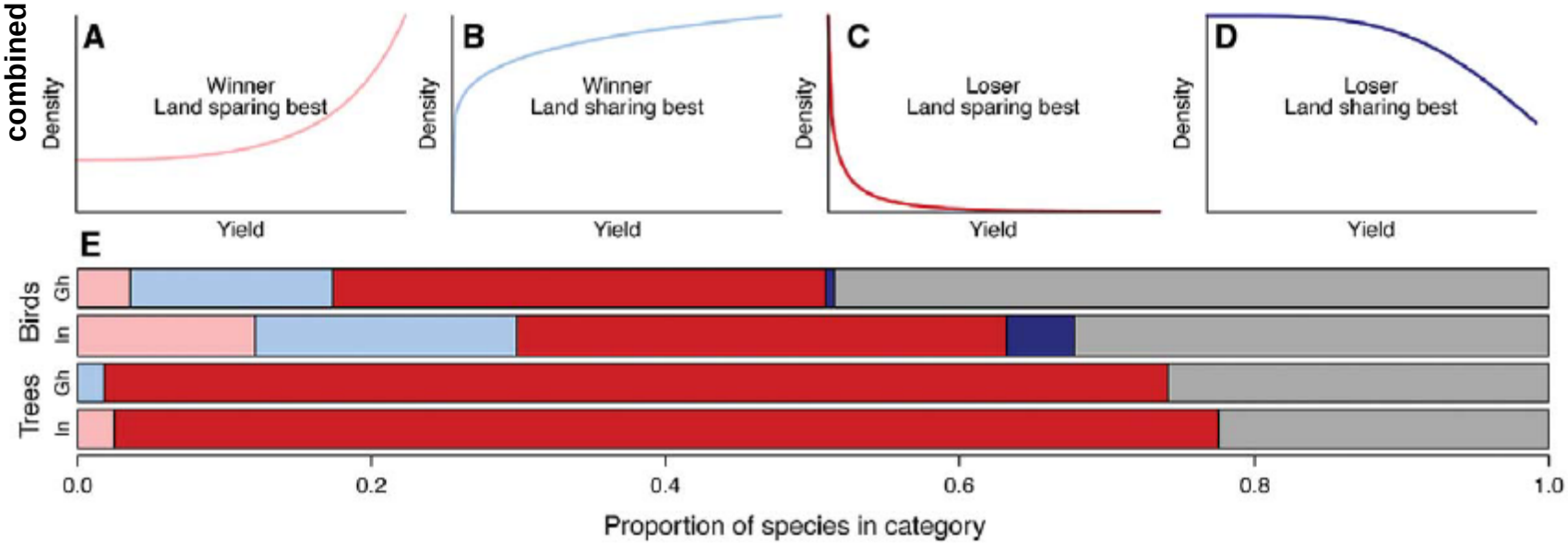
Trade-off between effects on aquatic vs. terrestrial ecosystems?

Land sparing or sharing?

- **Land sparing**: Higher yields on existing ag/bio lands can reduce expansion into wildlife habitat.
- **Land sharing**: Wildlife-friendly farming; humans an inextricable part of nature.

A-B) species with higher densities in managed lands than wildlands

C-D) higher densities in wildlands than managed lands



Phalan et al. 2011. Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. Science

Integrated Landscape Management / Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objective: Increase the biomass supply available for biofuel while reducing the cost and maintaining or improving sustainability.

Justification: The current BT2 identifies enough biomass to support the predicted growth in bioenergy but does not take into account important moderators such as transport distance, supply radius, supply quality and yearly variation. With these factors added in to the equation, we quickly move up the supply curves towards unrealizable costs for biofuel. This project is focused on increasing overall biomass supply while enhancing environmental sustainability.

Sub-field Profit Profile

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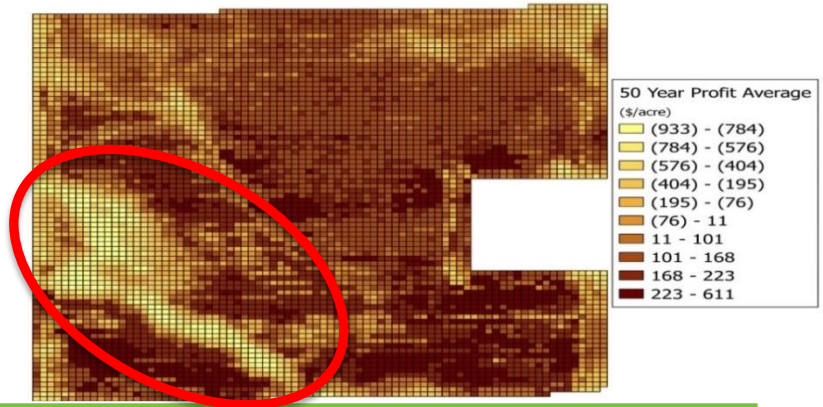
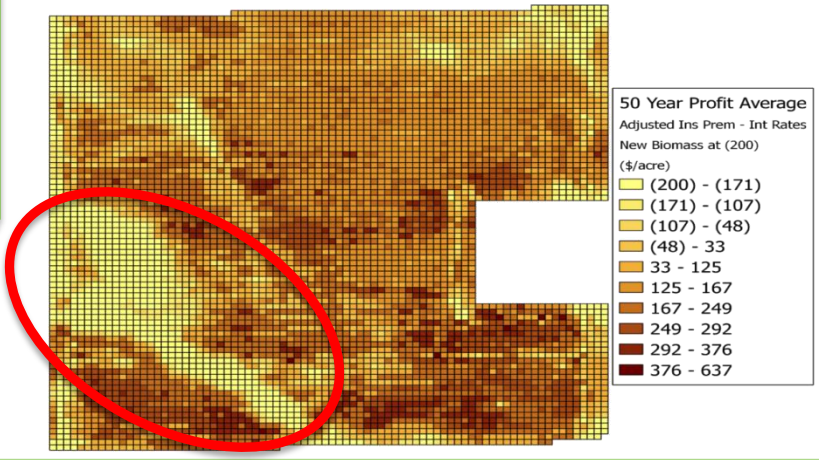


Three years of crop yield data calibrated with a crop growth model and run over 50 years of weather history on a 10 m grid.

Summary statistics for subfield profitability

Summary		
50 Year Yield Average:	170	bu ac^{-1}
50 Year Yield Standard Deviation:	38	bu ac^{-1}
Profit Average:	$47	$ ac^{-1}
Profit Standard Deviation:	$235	$ ac^{-1}
Years Profitable Average:	31	
Years Profitable Standard Deviation:	14	
Percentage of Field Profitable:	74%	

Subfield profitability assuming each grid cell operating at an average loss of 200 $ ac^{-1} or greater is converted to an energy crop which operates at that same 200 $ ac^{-1} loss.

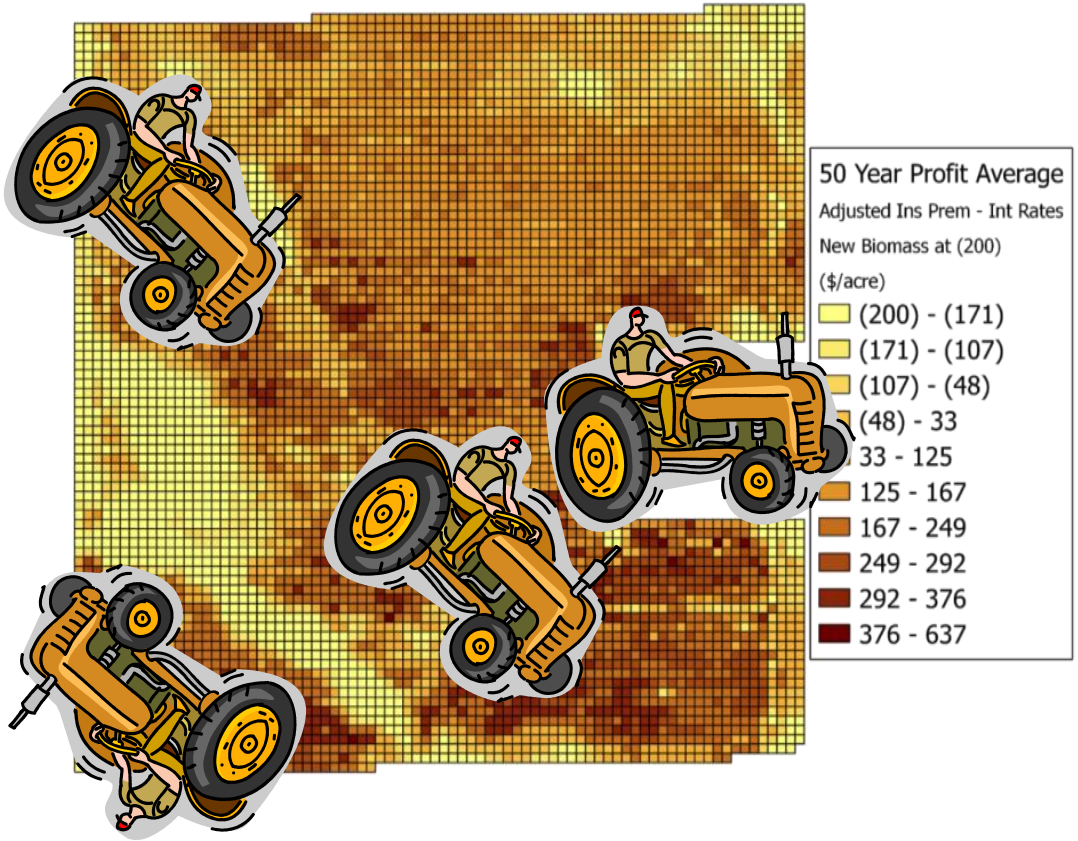


Summary statistics for subfield profitability

Summary		
New production at loss > $200/acre with adjusted ins prem's and int rates		
Profit Average:	$105	$ ac^{-1}
Profit Standard Deviation:	$149	$ ac^{-1}
Percentage of Field Profitable:	79%	

ADJACENCY

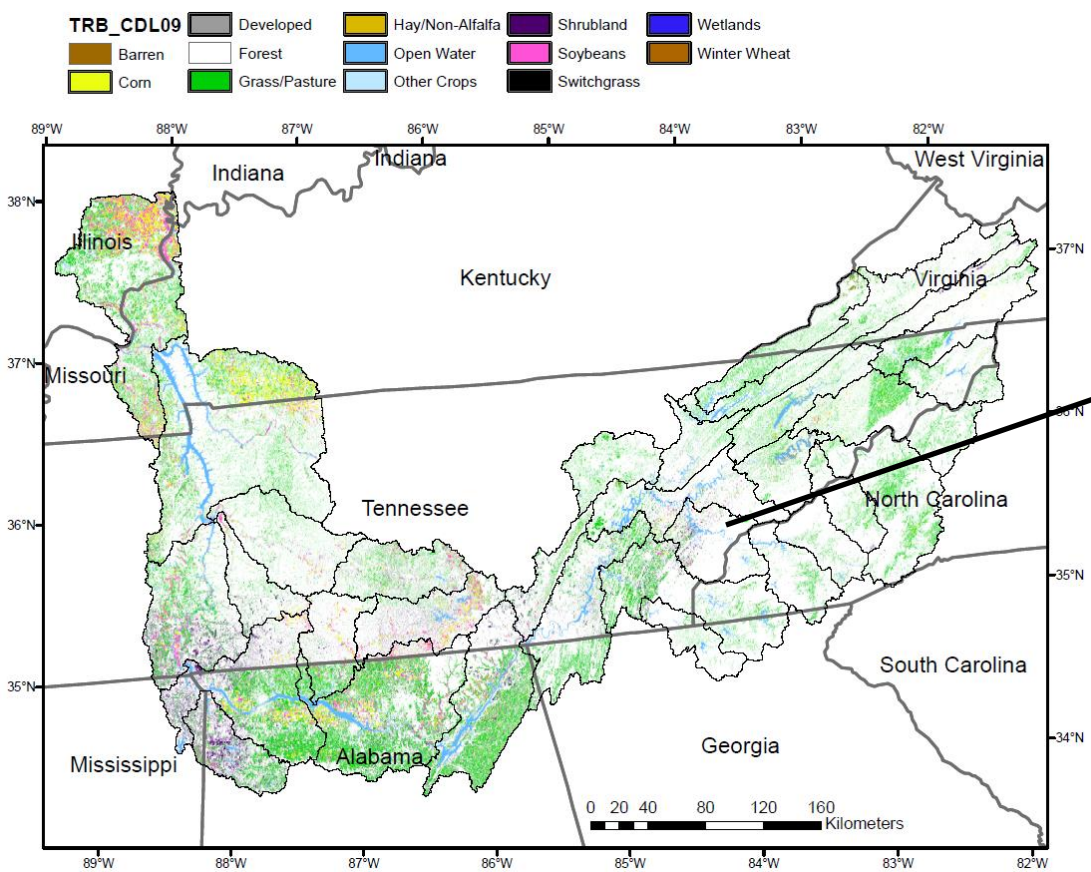
Economic example
(sub-field logistics)



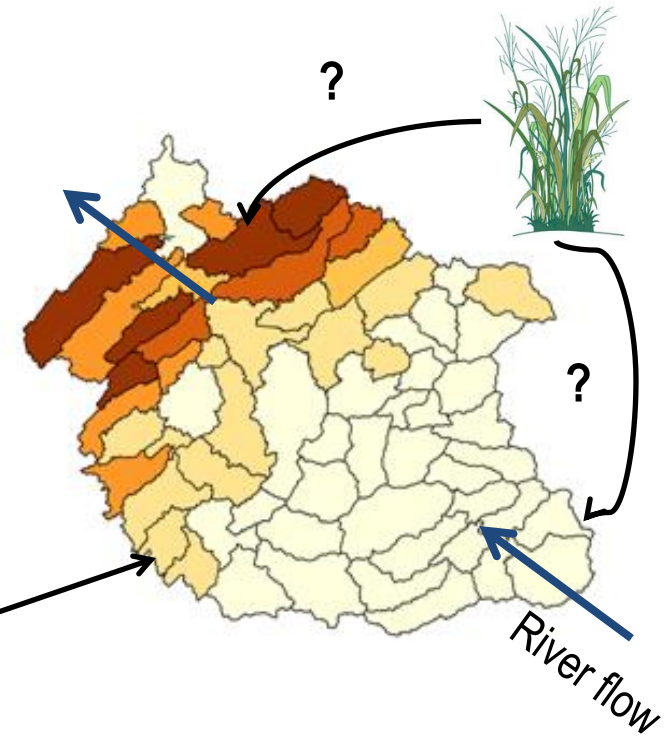
- Impractical for farmer to drive tractor around small, interspersed patches planted in perennial bioenergy crops.
- Logistics / labor cost is not considered in analysis.

ORNL BLOSM framework

Parish et al. (2012). Multimetric spatial optimization of switchgrass plantings across a watershed. Biofuels, Bioproducts and Biorefining 6(1), 58 - 72.



where to plant switchgrass?



Ecological traps

- Avoid creating habitat that attracts, but harms, wildlife.
- Patches of good habitat too small (minimum habitat size)
- Embedded in dangerous matrix
  - Exposure to contaminants (e.g., amphibians & atrazine)?
  - Low diversity in Amazonian forest fragments surrounded by 'hard' edges (Koh et al. 2009 TREE)
  - Stump extraction and beetles (Victorsson & Jonsell 2011)

Questions of scale

- At what spatial scale are conservation features most beneficial?
- At what scale does **intensification** lead to improved environmental sustainability?
- At what scale should **incentives** for conservation be designed?

SPATIAL SCALE

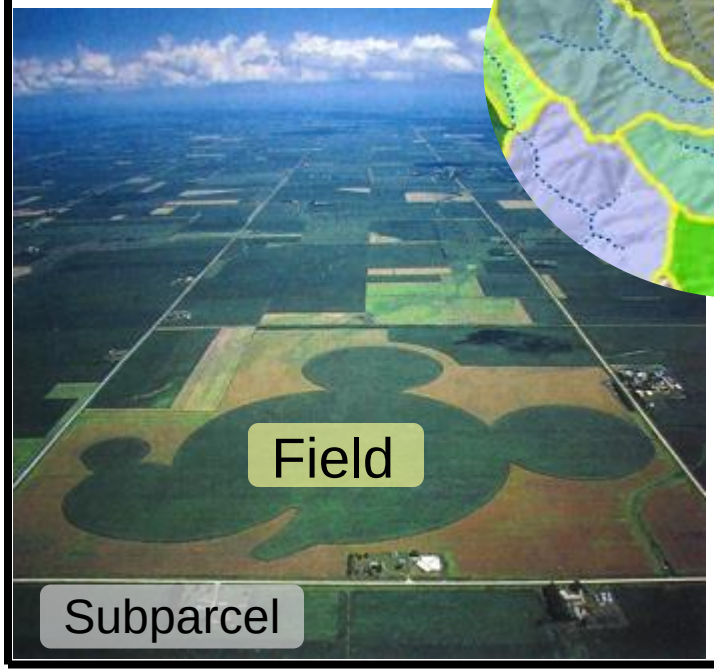
Pathways to Sustainability

Forecasting Water Quality & Biodiversity

Policy context

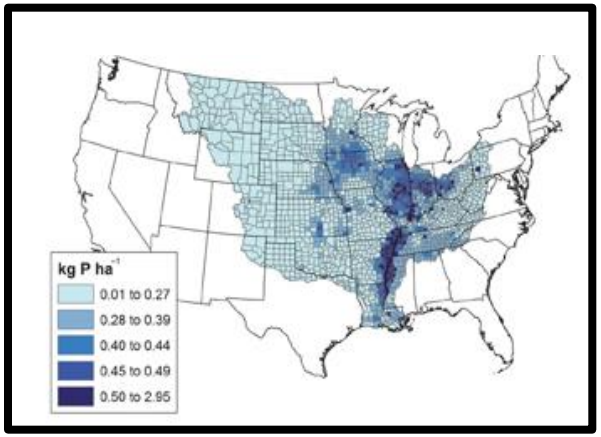
Indicator response

Decision making



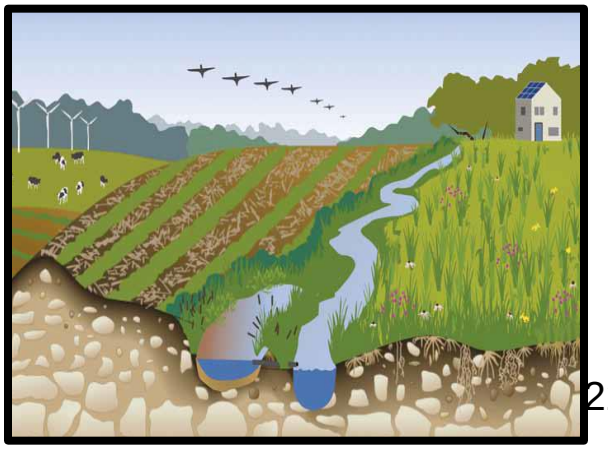
Spatial extent

Forecasting Water Quality

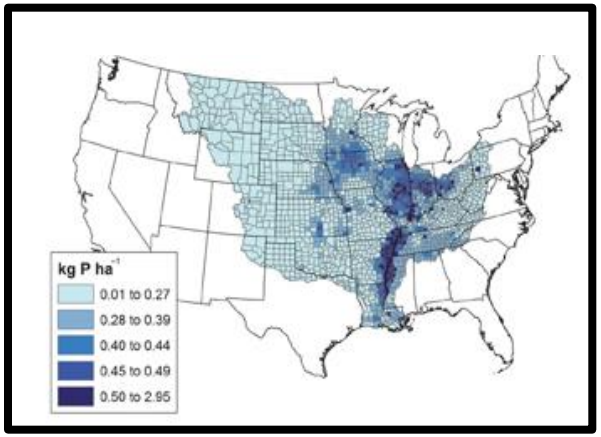


Forecasting Biodiversity

Pathways to Sustainability

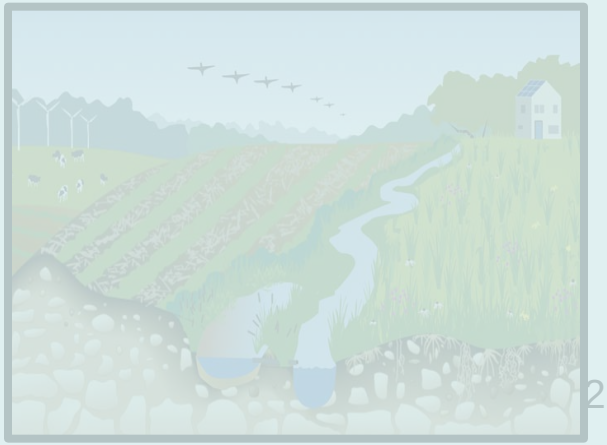


Forecasting Water Quality



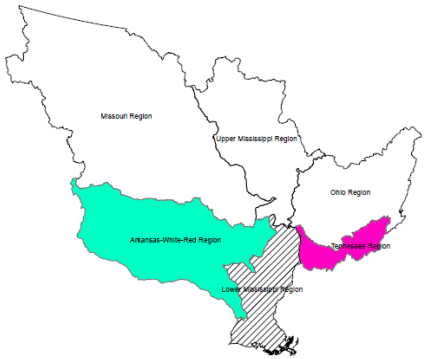
Forecasting Biodiversity

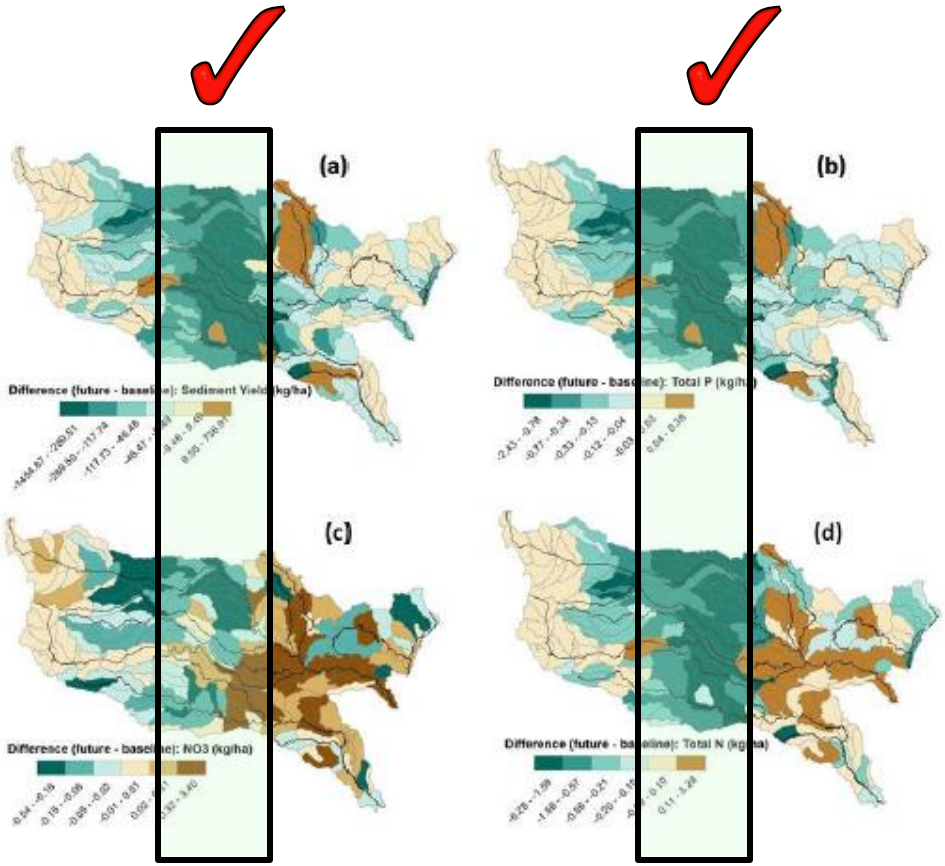
Pathways to Sustainability



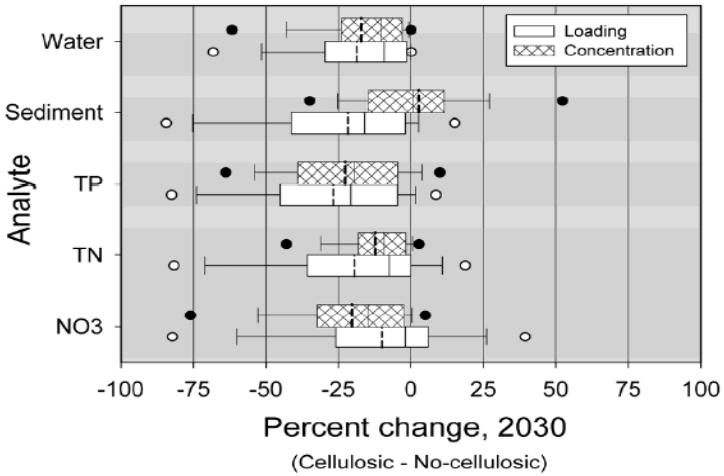
Forecasting Water Quality

- Baskaran, L.M., H.I. Jager, P. E. Schweizer, R. Srinivasan. 2010. Progress toward evaluating the sustainability of switchgrass production at a regional scale. American Society of Agricultural and Biological Engineers 53(5): 1547-1556
- Jager, HI, LM Baskaran, PE Schweizer, AF Turhollow, CC Brandt, R Srinivasan. In press. Forecasting changes in water quality in rivers associated with growing biofuels in the Arkansas-White-Red river drainage, USA. GCB Bioenergy



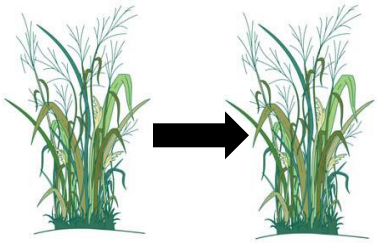


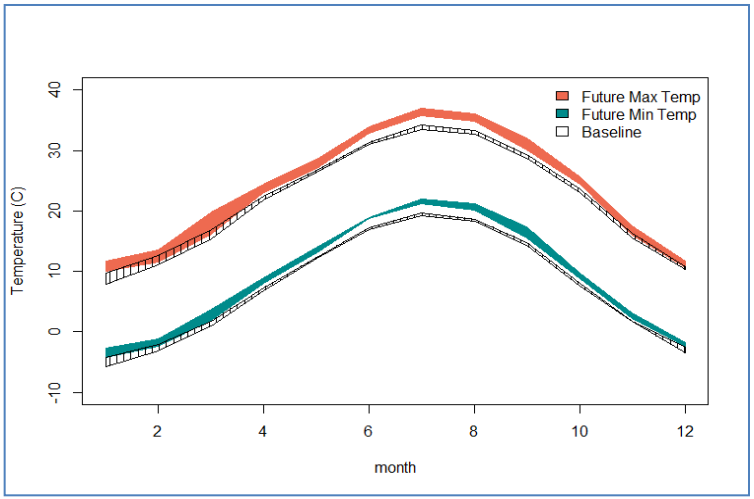
ORNL-ANL Mississippi River basin-scale collaboration

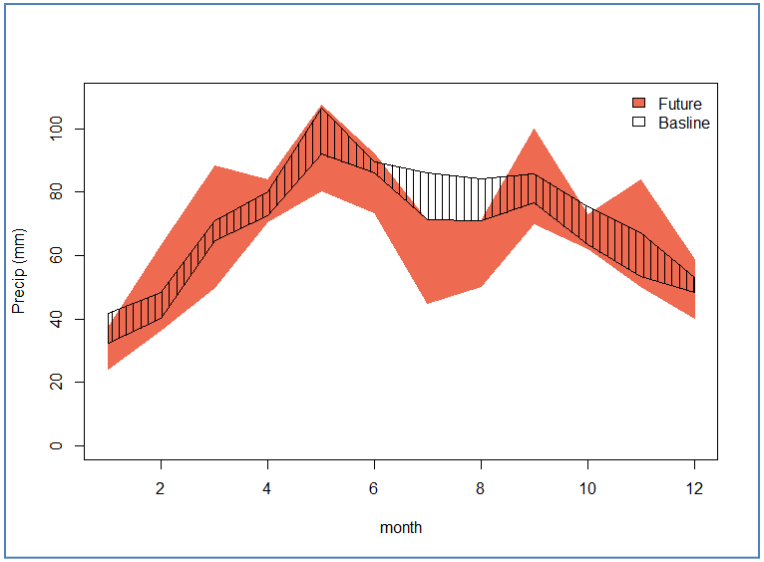


Even more advantageous under future climate

- Much higher switchgrass yields, *slightly higher nitrate in streams*.
- More variable but similar range of yields for winter wheat, *less variable and lower nitrate in streams*.







Beyond economic water quality targets

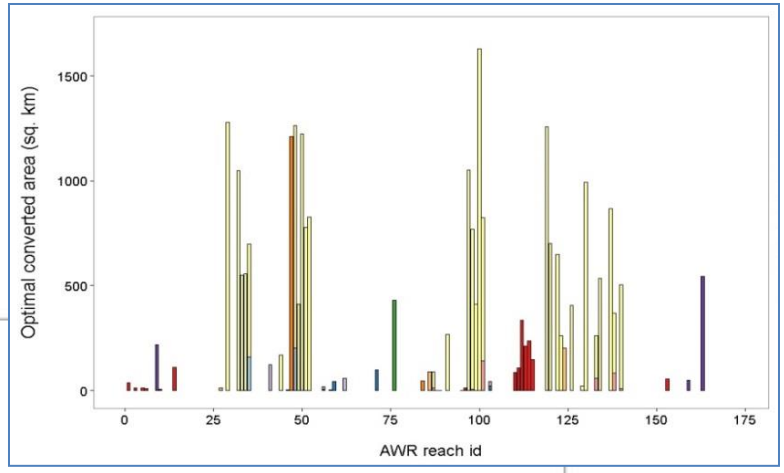
Spatial prioritization tool

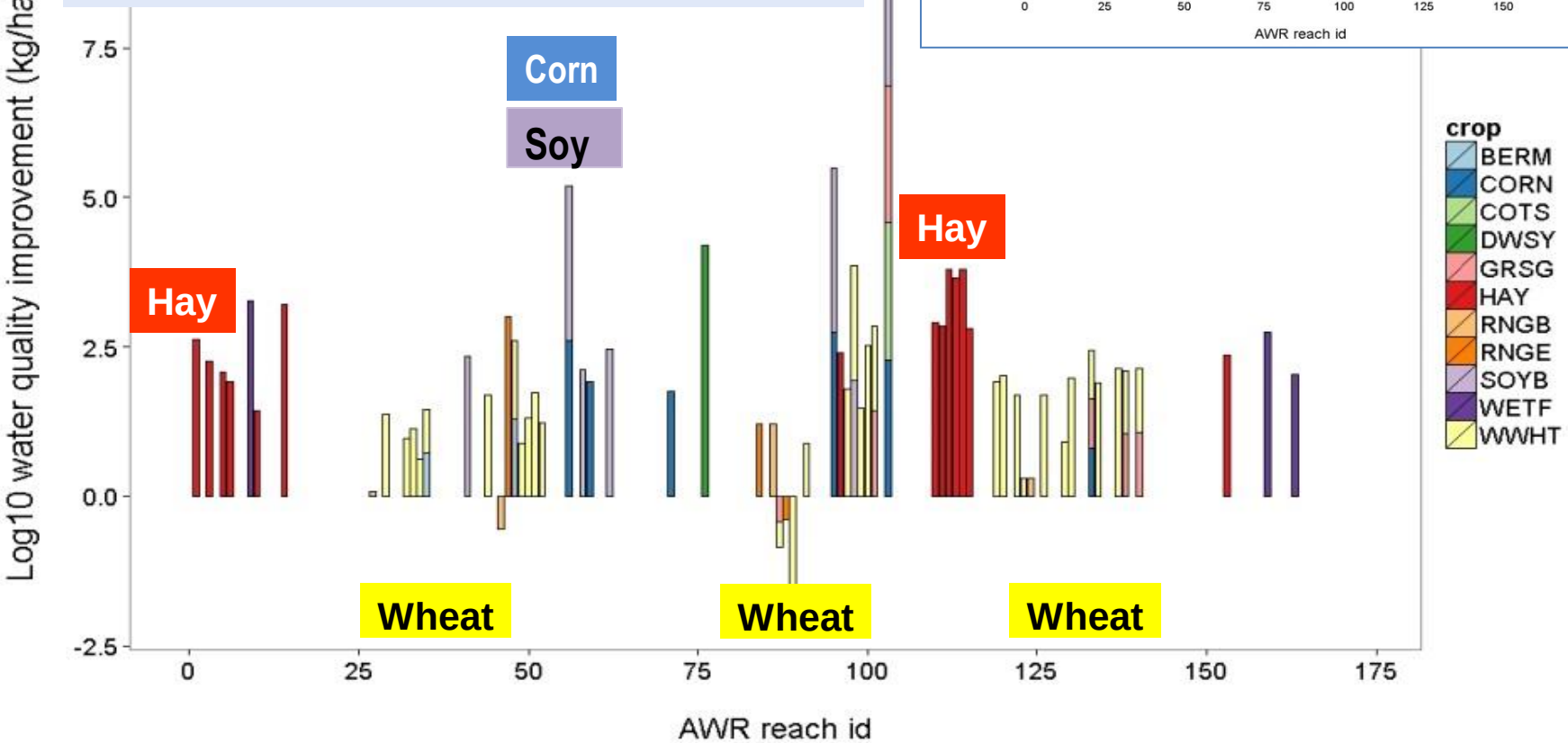
$$Minimize \sum_k Acv_k \left(\frac{\partial WQ}{\partial Acv_k} \right), \text{ subject to constraints:}$$

$$\sum_k Acv_k \le Area_{bio}(t_f) \equiv \text{BT2 future area in bioenergy crops}$$

$$Acv_k \le Area_k(t_0) \ \forall \text{ crops } k, \text{ where}$$

$$\text{Area of crop } k \text{ converted, } Acv_k \equiv Area_k(t_0) - Area_k(t_f)$$





TRADE-OFFS & COMPLEMENTARITIES

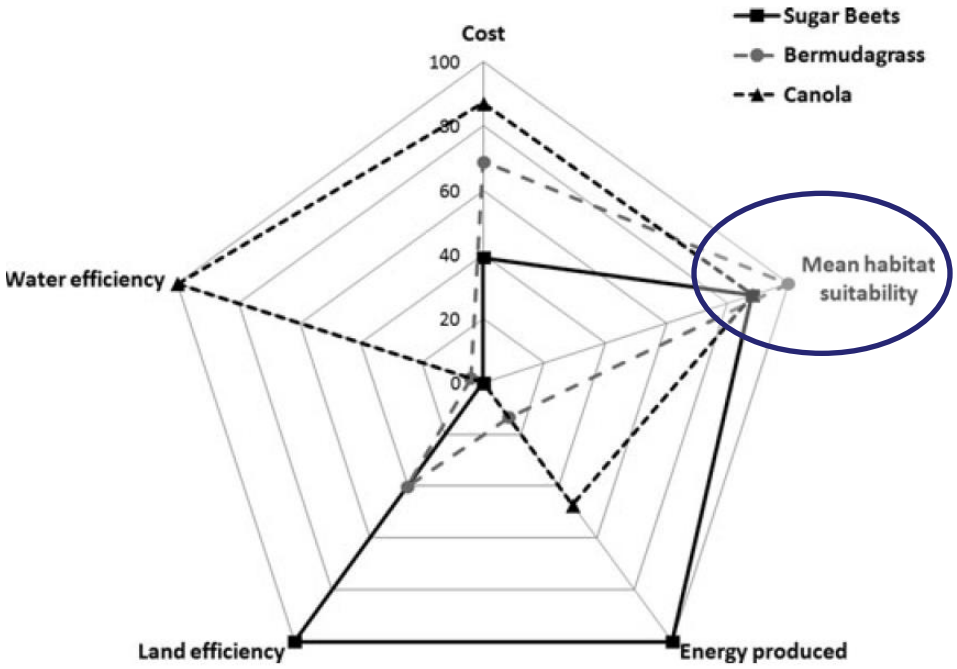
Trade-offs among sustainability indicators

California bioenergy crops

$$\text{Minimize } Z = \sum_{j=1}^{J} c_j * x_j + \sum_{i=1}^{I} \text{SPF}_i * p_i \qquad (1)$$

$$\text{Subject to} \sum_{j=1}^{J} a_{ij} x_j \geq r_i \qquad (2)$$

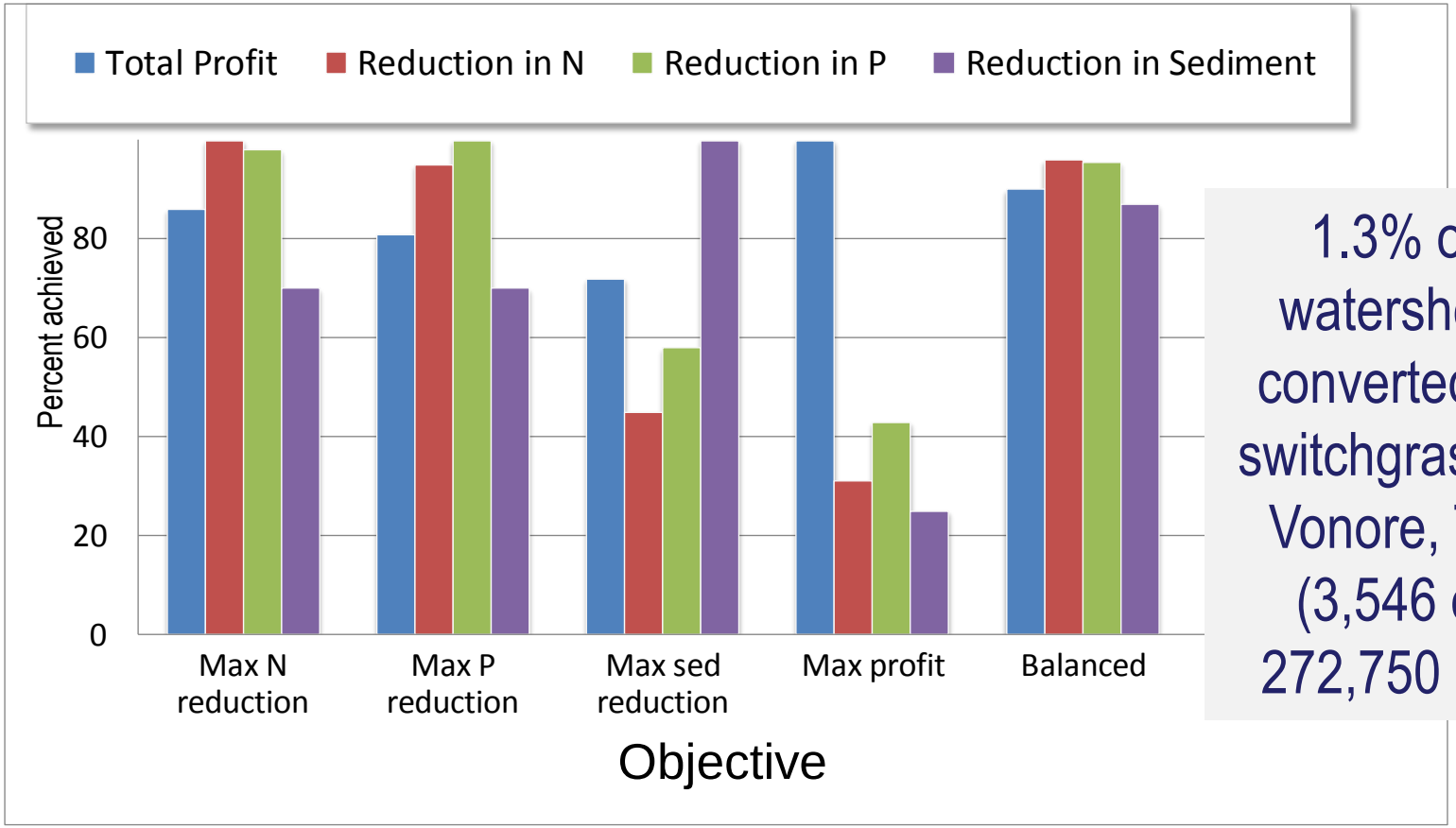
where a_{ij} is a measure of the amount of feature i in planning unit j (i.e., sections), x_j is a {0,1} variable that has a value of 1 if section j is selected and 0 otherwise. Each section has a cost c_j, and each feature is assigned a desired target r_i. The second term in Eqn (1) is a penalty for failing to achieve the target constraints in Eqn (2) and is comprised of a penalty factor (SPF) for feature i multiplied by difference between the desired and achieved amount of the feature in the final solution (p_i, the 'shortfall' for feature i). We included features for biofuel and the wildlife Species of Special Concern. The targets for biofuel



aij = amount of biofuel produced
or net change in species habitat suitability

Stoms 2012 Minimize-Habitat-Loss Scenario

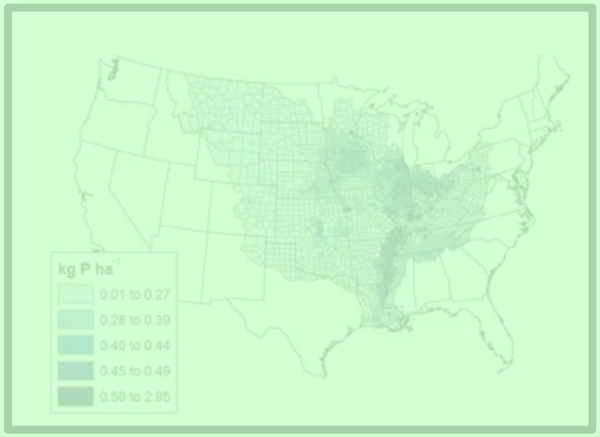
BLOSM framework
Spatial optimization w/ multiple objectives



1.3% of watershed converted to switchgrass in Vonore, TN (3,546 of 272,750 ha)

Parish et al. (2012). Multimetric spatial optimization of switchgrass plantings across a watershed. Biofuels, Bioproducts and Biorefining 6(1), 58 - 72.

Forecasting Water Quality



Forecasting Biodiversity

Pathways to Sustainability

Biodiversity trade-off analysis

risk species. Net returns in each county, i, are estimated using a Biomass Profitability Index (BPI):

$$BPI_i = Y_i * \sum_c L_{i,c} - \sum_c (R_{i,c} * L_{i,c}),$$

where Y_i is the average biomass yield (Mg ha^{-1}) in county i predicted by the BIOCRO crop growth model. $L_{i,c}$, is the acreage (ha) of land category c in county i allocated to SGBC production as determined by the model. $R_{i,c}$ is the (exogenous) land rental rate for each county and land category. The first term in the BPI represents the total biomass (Mg) produced in county i, based on the SGBC yields and land availability. The second term imposes an economic penalty, determined by the rental rate, for higher cost land. The optimization problem can then be written as follows:

$$\max_{L_{i,c}} \sum_i BPI_i$$

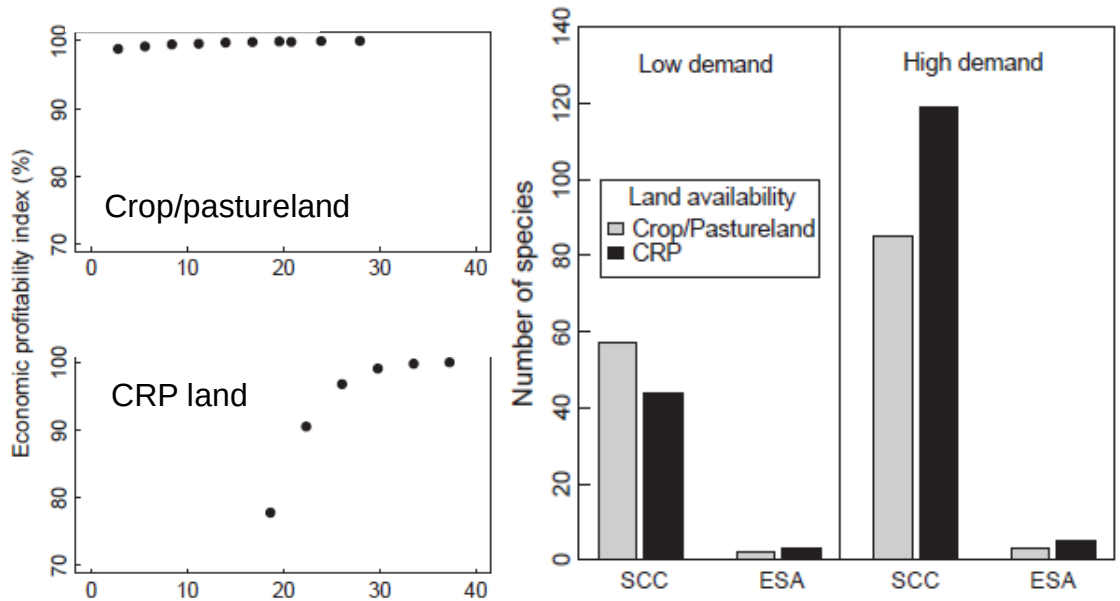
subject to:

$$L_{i,c} \leq \bar{A}_{i,c} \quad \text{(C1)}$$

$$\Sigma_i (Y_i \Sigma_c L_{i,c}) = B \quad \text{(C2)}$$

$$\Sigma_{i,k} S_{i,k} \leq \bar{S} \quad \text{(C3)}$$

In this formulation, the model predicts SGBC acreage ($L_{i,c}$) for each country and land category by maximizing the national BPI subject to constraints on land availability (C1), biomass demand (C2), and species conservation objectives (C3). $\bar{A}_{i,e}$ is the total available acreage in county i for each land category. Constraint 1 ensures that total SGBC production in each county does not exceed that county's eligible agricultural land base. B is total cellulosic biomass demand (Mg), determined by the supply of biomass required for the cellulosic biorefining industry to meet a national biofuel production target. $S_{i,k}$ is binary variable identifying whether a particular at-risk species, k, is present in county i. $S_{i,k} = 0$ if (i) a particular species has not been observed in that county (based on the Natureserve database); or (ii) no land is allocated in county i for SGBC



% species impacted

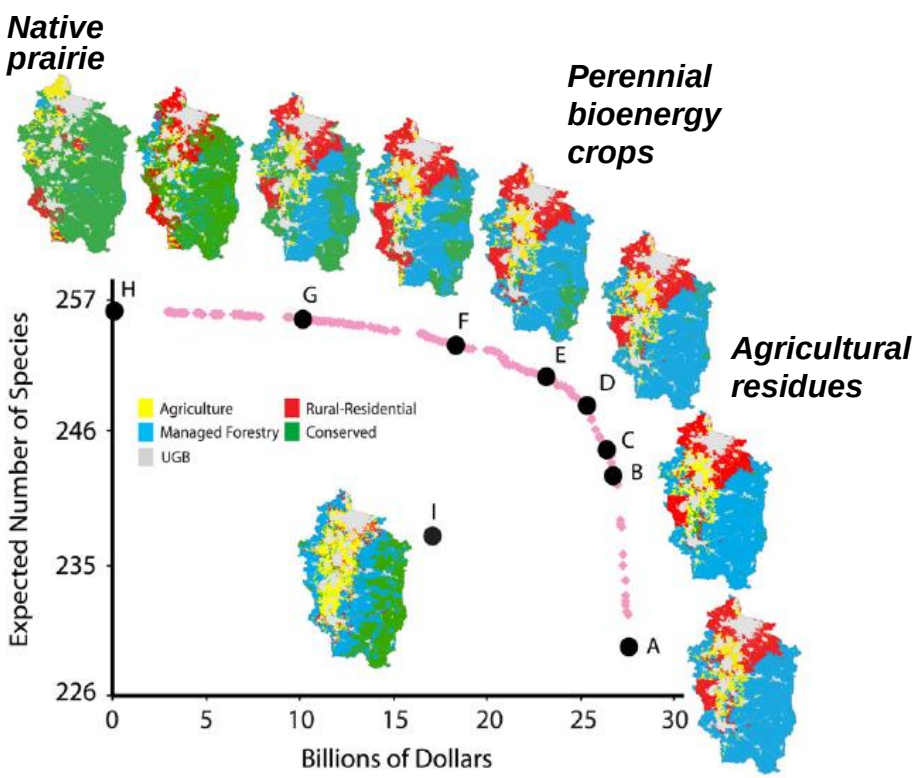
relax constraint

- National scale
- Species of conservation concern, SCC: *birds, amphibians, lizards, mammals*
- Habitat uses: *cropland or pastureland*

Evans et al. in press

Trade-offs

Bioenergy and Biodiversity



Hypothetical example of a frontier

Unannotated Source: Polasky, White et al. (2008)

Find $Acv_{i,k}$ that maximize energy & biodiversity:

1) $Z_{energy} = Y_i \sum_k Acv_{i,k}(1 - R_{i,k})$

2) $Z_{biodiversity} = \sum_{i,k} S_{i,k}$

Subject to constraint:

$Acv_k \leq Area_k(t_0)\ \forall$ crops k, where

Area of crop k converted, $Acv_k \equiv Area_k(t_0) - Area_k(t_f)$

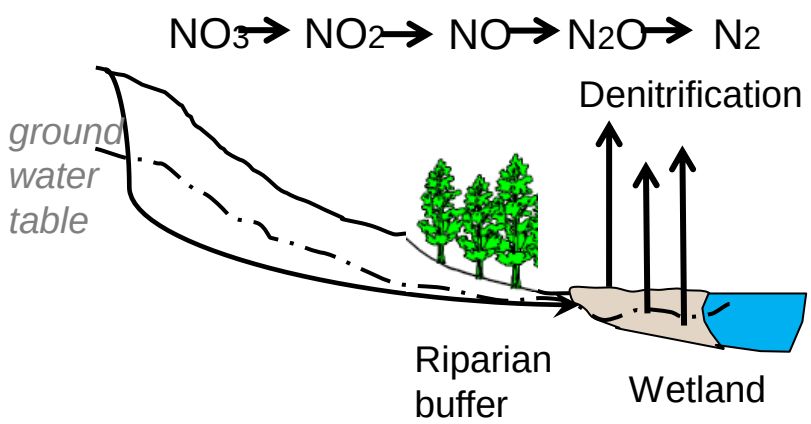
Proposed ORNL analysis

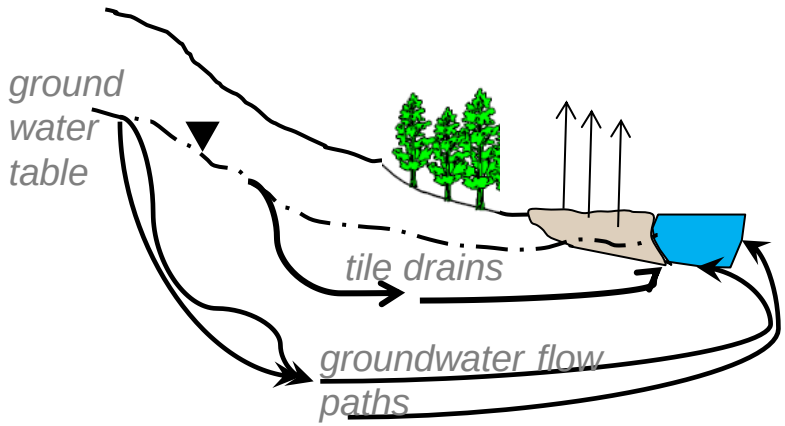
- Consistent with BT2 assumptions about land rent
- Heuristic search for non-dominated frontier, not LP
- Refine to add minimum habitat patch size (ecological traps).
- Water quality as 3rd objective

Complementarities

Water Quality and Biodiversity

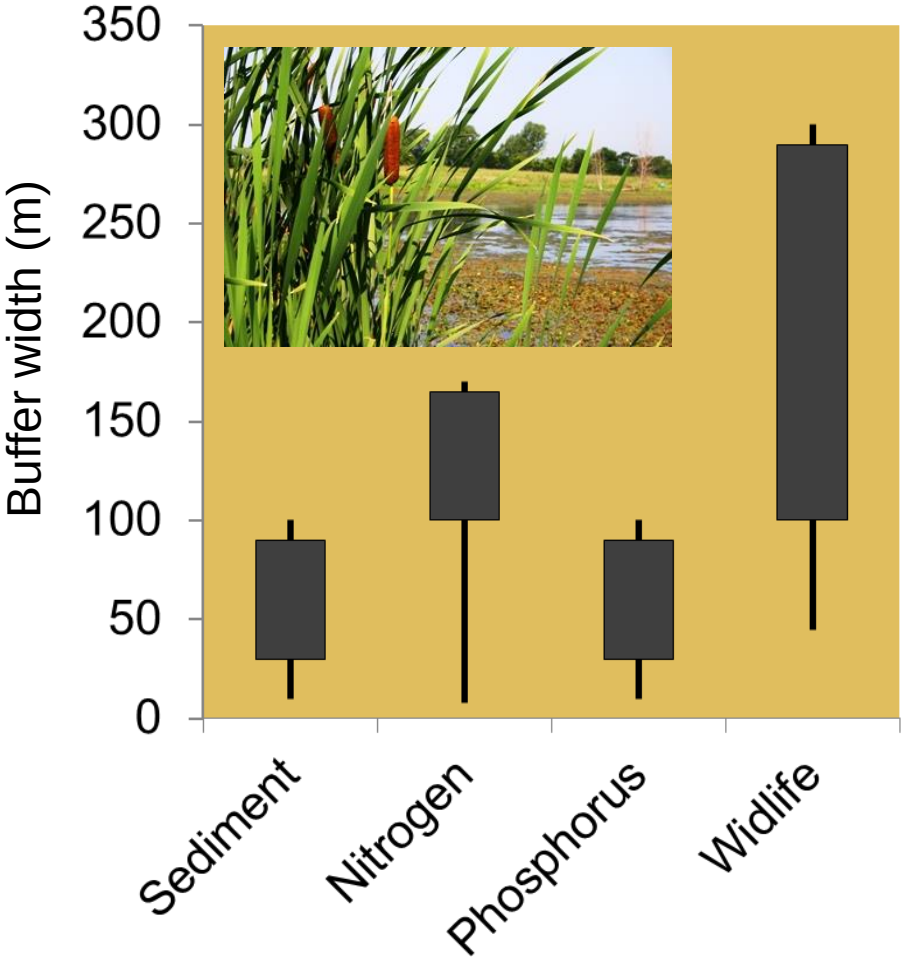
- In general, we expect spatial concordance between WQ and biodiversity outcomes for aquatic species
- Counter-example:
  - Water-table control of tile drained fields and wetlands both promote denitrification.
  - Only wetlands benefit wildlife.





Wetlands and buffers

- Wildlife require wider riparian buffers than water quality.
- However, some taxa do not benefit from buffers
  - Waterfowl prefer crop stubble, not riparian buffer vegetation.



Source: Richard Lowrance in Grofmann presentation, EPA meeting.

Example 1.

Walnut Creek, IA

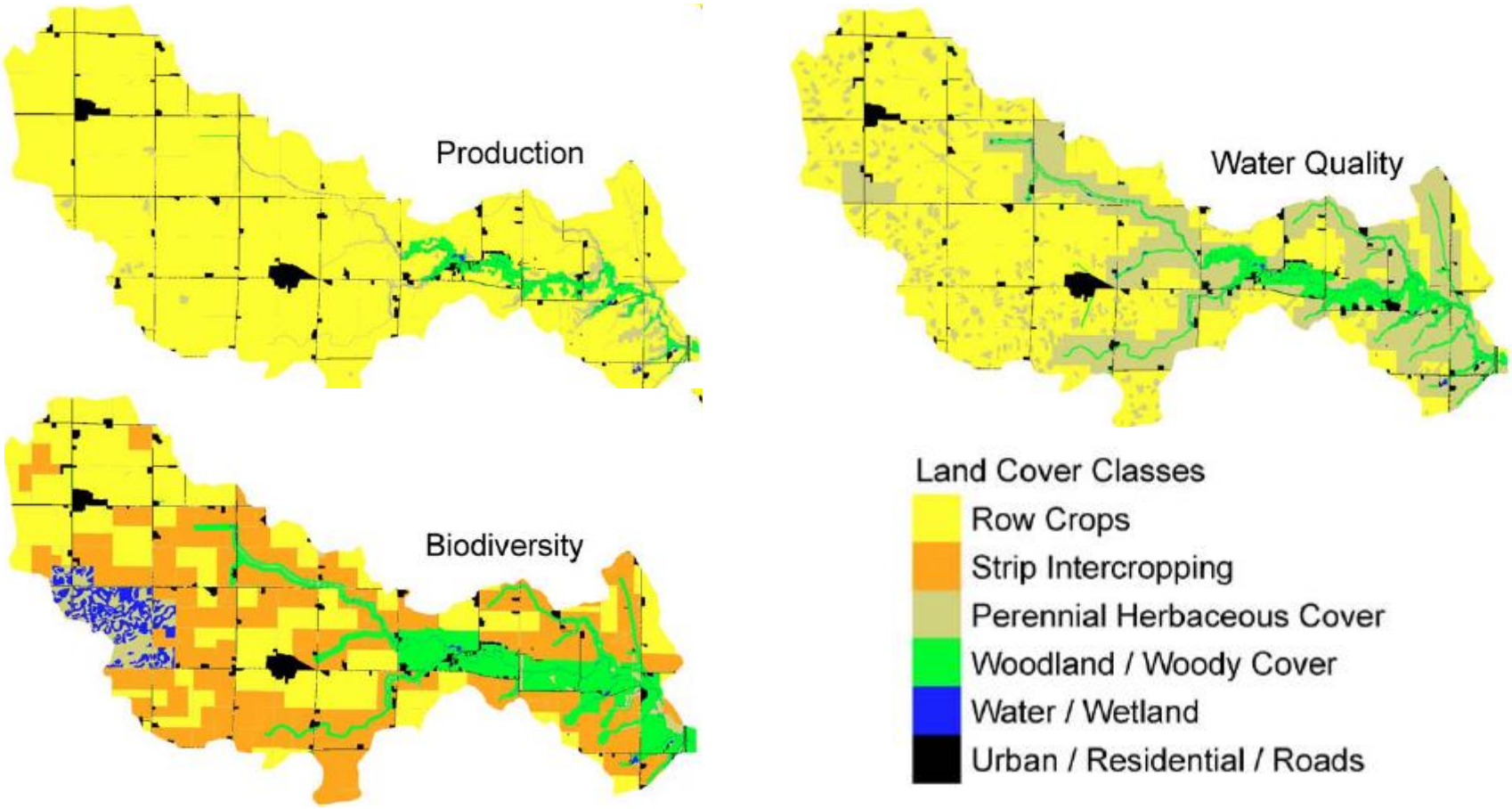


Figure 2. Present landscape (top right) and designed alternative future scenarios for Walnut Creek watershed. Note the increase in land area in row crops at the expense of perennial cover for the Production scenario; the increased amount of land in perennial cover (pasture and forage crops) as well as wider riparian buffers in the Water Quality scenario; and the strip intercropping, wide riparian buffers and extensive prairie, forest and wetland restorations in the Biodiversity scenario.

Santlemann et al. 2004

Example 2.

Buck Creek, IA

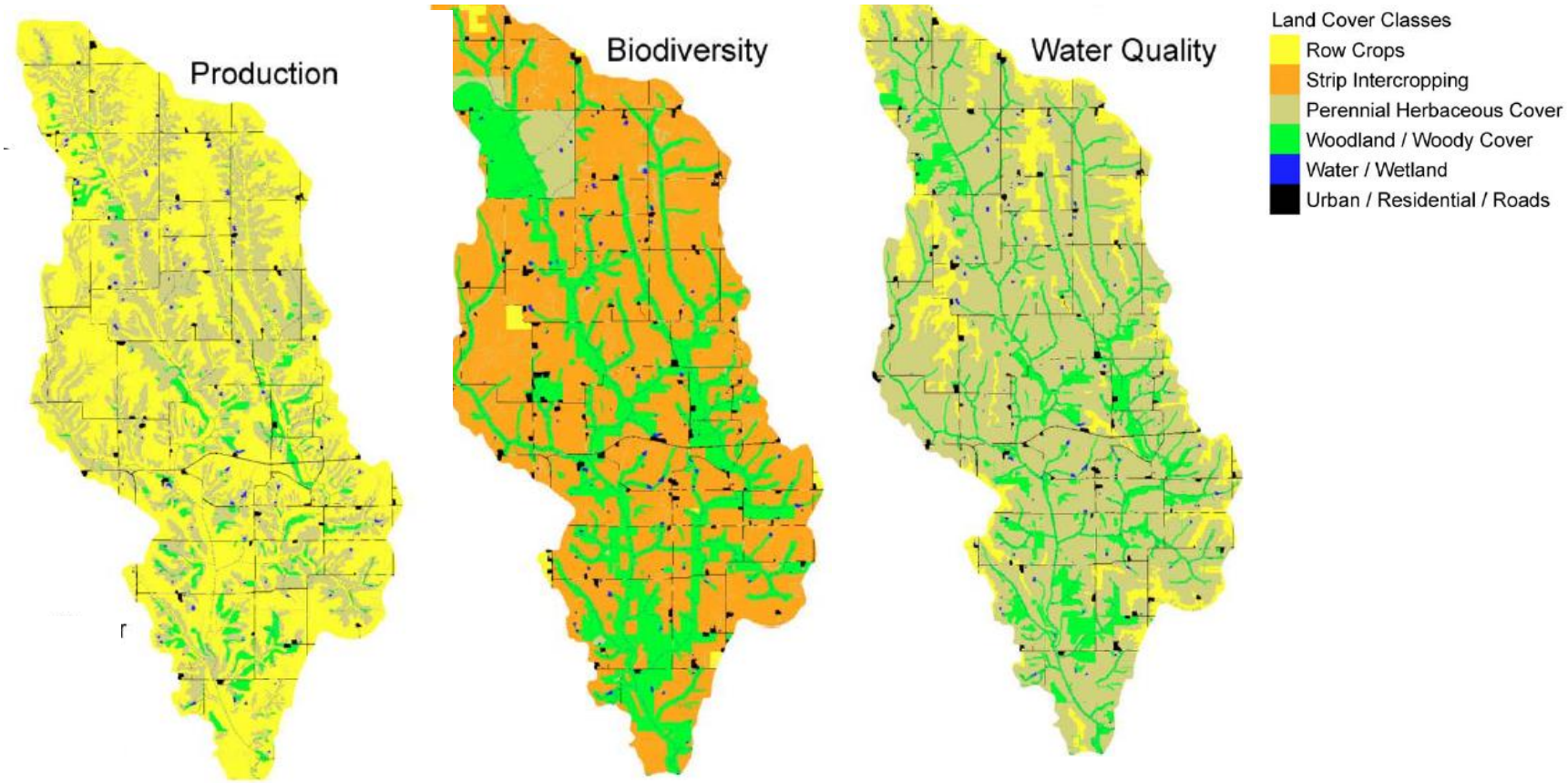
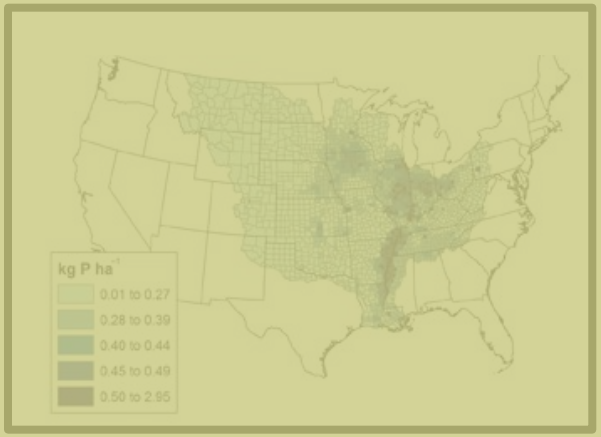


Figure 3. Present landscape (top left) and designed alternative future scenarios for Buck Creek watershed. Note scenario features similar to those for Walnut Creek but applied to a different landscape (e.g., the physiography of the watersheds led to the design of forest, savanna, and upland prairie reserves in Buck Creek rather than the riparian forest and prairie/ prairie pothole wetlands which comprised the reserves in Walnut Creek watershed).

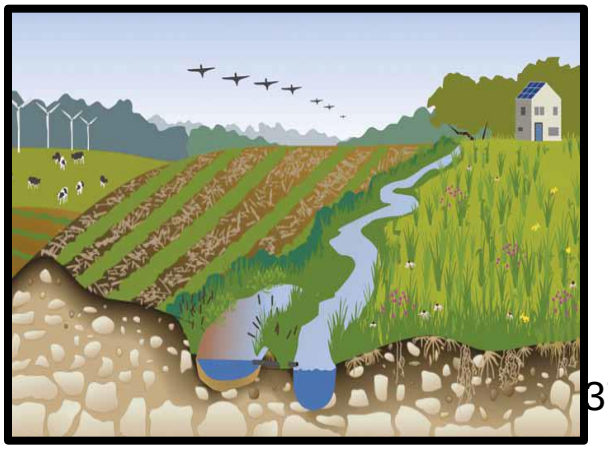
Santlemann et al. 2004

Forecasting Water Quality



Forecasting Biodiversity

Pathways to Sustainability

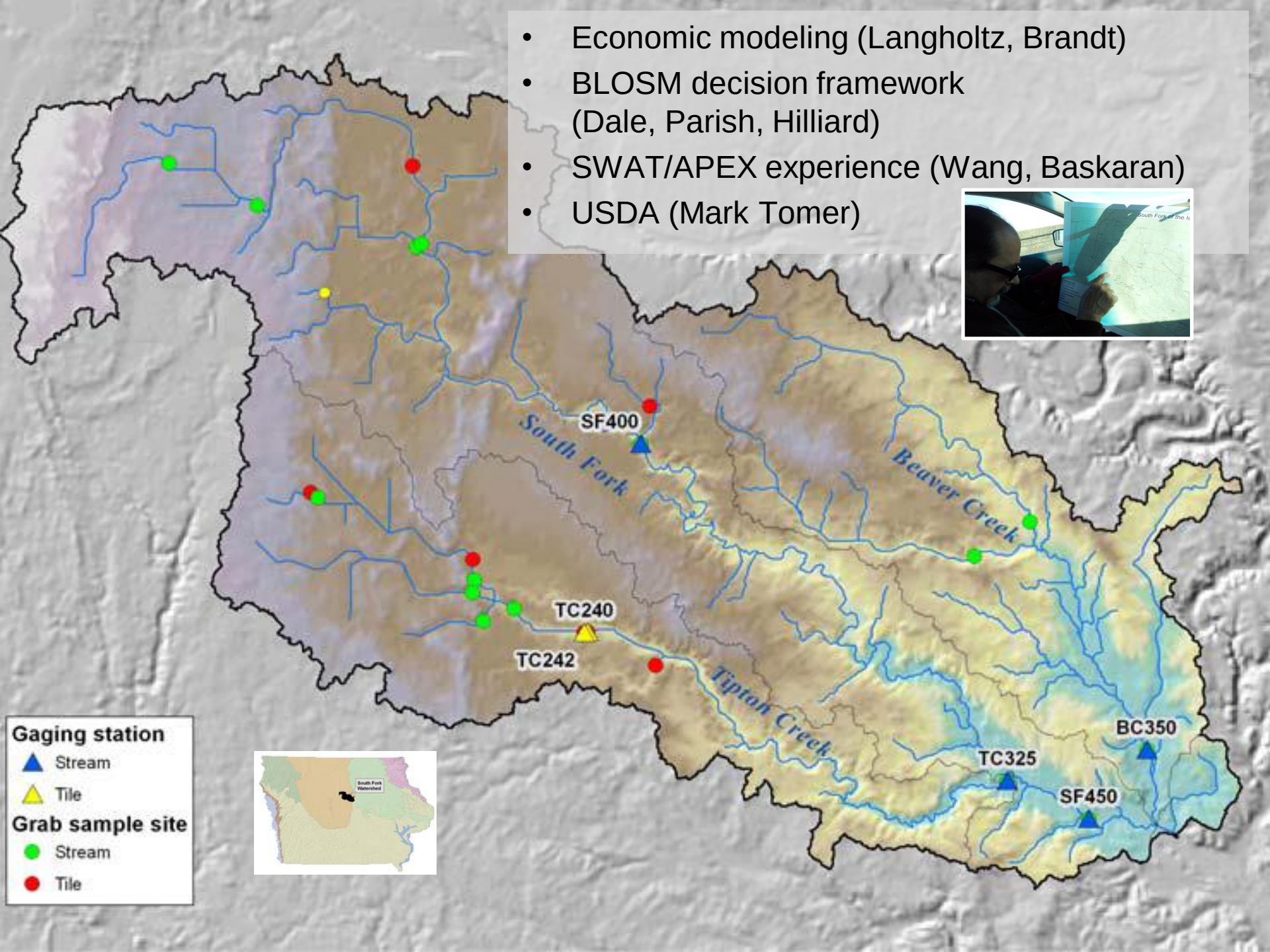


Pathways to sustainable decisions

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Sustain-ability indicator	Tillage / bailing practice	Crop / buffer placement	Stover removal	Fertilizer applied	Pesticide applied	Tile drain measure	DOE Lab
Compo-sition							INL
Yield		X	X	X	X		INL
Soil carbon		X	X				INL
Sediment		X	X				ORNL, ANL
Nitrate		X	X	X	X		ORNL, ANL
Phosphate		X	X	X	X		ORNL, ANL
Biodiversity		X	X	X	X		ORNL
Min base flow			X				ANL
Lab (scale) p=parcel or s=subparcel		INL (s) ORNL (p)	INL (s)	ORNL (s)	ORNL (p)		

- Economic modeling (Langholtz, Brandt)
- BLOSM decision framework (Dale, Parish, Hilliard)
- SWAT/APEX experience (Wang, Baskaran)
- USDA (Mark Tomer)



APEX

Rule extraction

- Spatial optimization is not the last step.
- Extract rules from solutions
- Compare rules extracted from BLOSM-APEX optimization solutions against those now assumed in the Integrated Landscape Management tool (>34% highly erodible; distance to stream<200 m).
- **Rules will permit generalization to other locations.**
- **Rules will facilitate optimization in other locations.**

Future directions

- Optimization under uncertainty, i.e., minimize the risk of production < P, biodiversity < B (chance constraints).
- Consideration of connectivity

Summary

- **River basin scale:** Identified one promising region, searching others
- **Watershed scale:** Developing tools for designing sustainable energy landscapes

Questions?

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