Supply Chain Design for Nutrient Management and Harmful Algal Blooms Minimization

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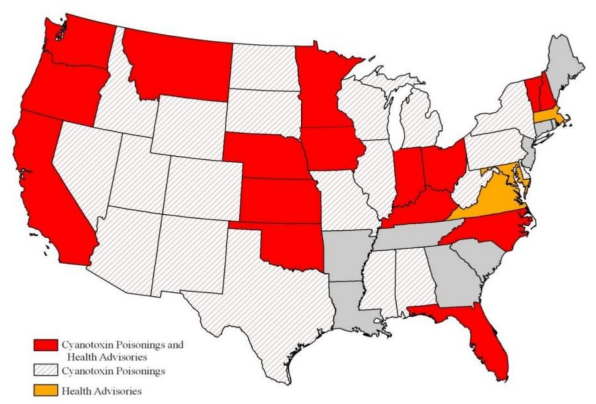
Motivation

Harmful Algal Blooms (HABs)

- ☐ Health threats
- Toxins to humans: e.g. microcystin-LR can lead to liver cancer
- Toxins to aquatic lives
- Other acute health effects: e.g. abdominal pain, fever etc.
- ☐ Economic impacts
- Tourism loss: ~$100,000,000 per year
- Fishing loss: >$ 10,000,000 per year (epa.gov)
- ☐ Aesthetic issues:
- Odor and color



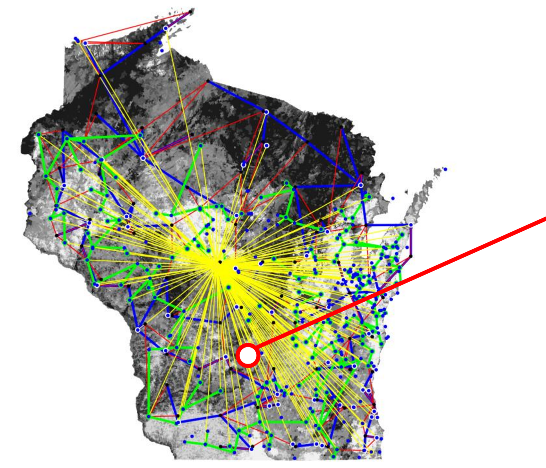
36 states reported human or animal poisonings associated with cyanotoxins in 2009 (Graham 2013)

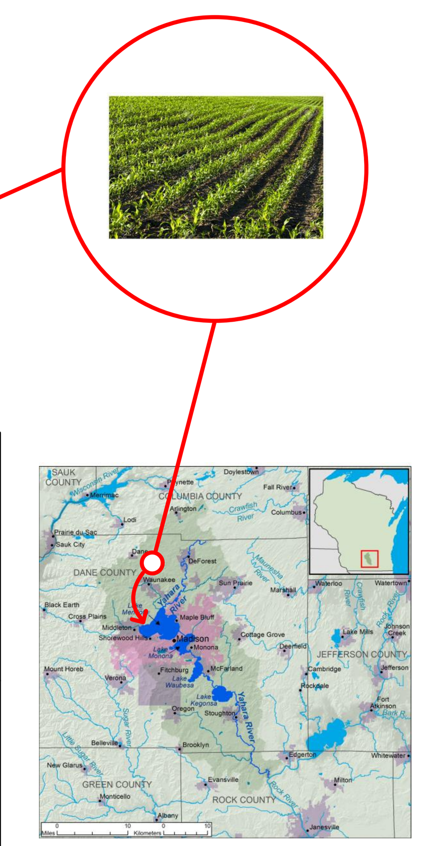
A picture of HAB (Cyanobacteria)

Supply Chain (SC) Design and Optimization

- A systematic approach to study organic waste management and nutrient management
- Sustainable supply chain design: compatible with some LCA indicators (e.g. eutrophication potential)
- Lack of end-point effect analysis for decision makers

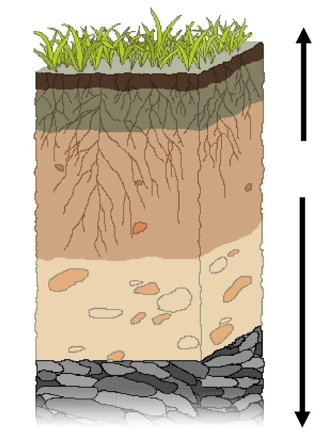
Modeling Framework: From Nutrient Pollution to Algal Blooms





Supply chain design for organic waste management
- Transportation logistics
- Technology placement
- Economic assessment
- Environmental assessment

Nutrient transport model
- Amount of nutrients that reach one waterbody
- Transport time

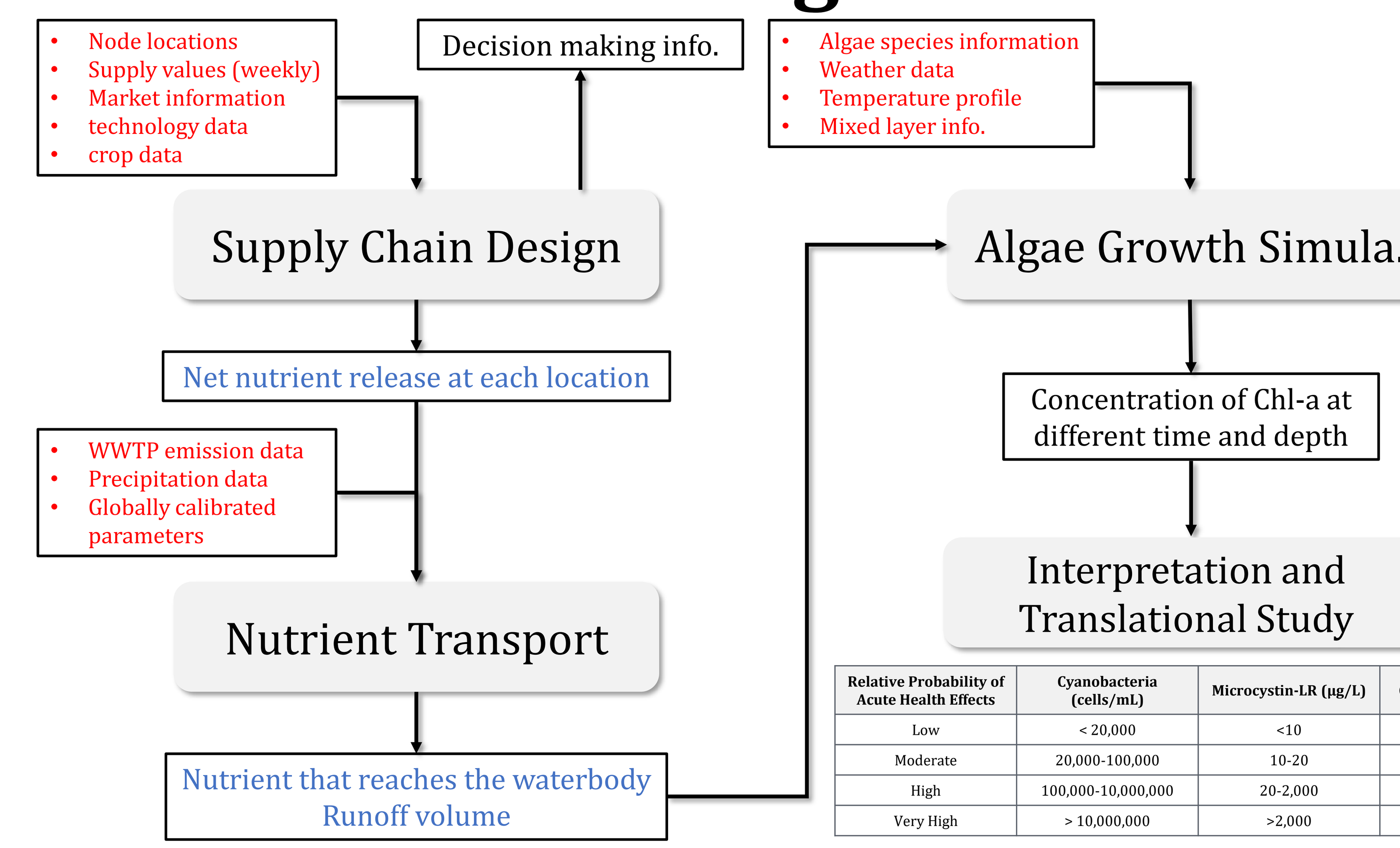


Nutrient output:
Crop uptake
Surface runoff
Leakage

Nutrient input:
Manure
Fertilizer
Fixation
Deposition

Onsite application of organic waste
- Crop type and amount
- Time for application
- Nutrient management plan (NMP)

Algae simulation:
- Amount of Chl-a at different time
- Feedback for nutrient management strategies



Relative Probability of Acute Health Effects	Cyanobacteria (cells/mL)	Microcystin-LR (μg/L)	Chlorophyll-a (μg/L)
Low	< 20,000	<10	<10
Moderate	20,000-100,000	10-20	10-50
High	100,000-10,000,000	20-2,000	50-5,000
Very High	> 10,000,000	>2,000	>5,000

Supply Chain Model

$$I_{i,p,\tau-1} + s_{i,p,\tau} + \sum_j f_{j,i,p,\tau} + \sum_t g_{i,t,p,\tau} = I_{i,p,\tau} + d_{i,p,\tau} + \sum_j f_{i,j,p,\tau} \quad \forall i,p,\tau$$

$$g_{i,t,p,\tau} = \frac{\alpha_{t,p}}{\alpha_{t,p_{ref(t)}}} g_{i,t,p_{ref(t)},\tau} \quad \forall i,t,p,\tau$$

$$y_{i,t} \cdot C_t \le g_{i,t,p_{ref(t)},\tau} \le 0 \quad \forall i,t,p,\tau$$

$$C_{trans} = \sum_{i,j,p,\tau} f_{i,j,p,\tau} D_{i,j} C_{trans,p}$$

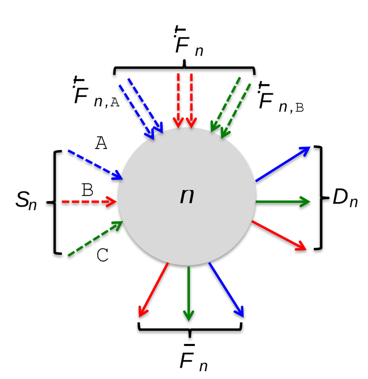
$$C_{op} = \sum_{i,t,\tau} g_{i,t,p_{ref(t)},\tau} C_{op,t}$$

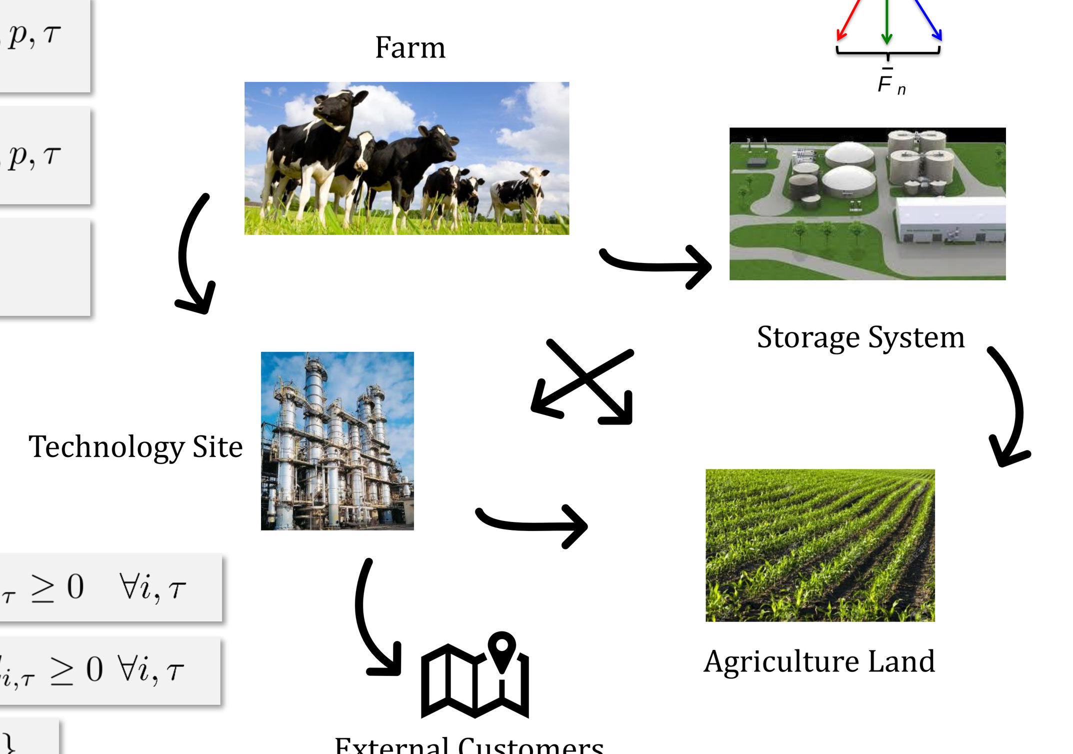
$$C_{inv} = \frac{1}{Life} \sum_{i,t} y_{i,t} C_{inv,t}$$

$$TP_{i,\tau} = ferP_{i,\tau} + Pe_p \cdot d_{i,p,\tau} - Pd_{i,\tau} \ge 0 \quad \forall i,\tau$$

$$TN_{i,\tau} = ferN_{i,\tau} + Ne_p \cdot d_{i,p,\tau} - Nd_{i,\tau} \ge 0 \quad \forall i,\tau$$

$$\min \{C_{inv}, C_{op}, C_{trans}, \sum TP, \sum TN\}$$





Nutrient Transport Model

- **NEWS2 Watershed Model**

Point sources:

$$\mathrm{RSpnt}_F = \mathrm{FE}_{pnt,F} \cdot \mathrm{RSpnt}_E$$

$$\mathrm{RSpnt}_E = (1 - \mathrm{hw}_{frem,E}) \cdot I \cdot \mathrm{WShw}_E$$

Diffusive (non-point) sources:

$$\mathrm{RSdif}_F = \mathrm{RSdif}_{expl,F} + \mathrm{RSdif}_{ec,F}$$

$$\mathrm{RSdif}_{ec,F} = \mathrm{f}_F(\mathrm{R}_{nat}) \cdot \mathrm{EC}_F$$

For DIP: $\mathrm{f}_F(\mathrm{R}_{nat}) = \left[1 + \left(\frac{R_{nat}}{a_F}\right)^{-b_F}\right]^{-1}$ For others: $\mathrm{f}_F(\mathrm{R}_{nat}) = (\mathrm{R}_{nat})^{a_F}$

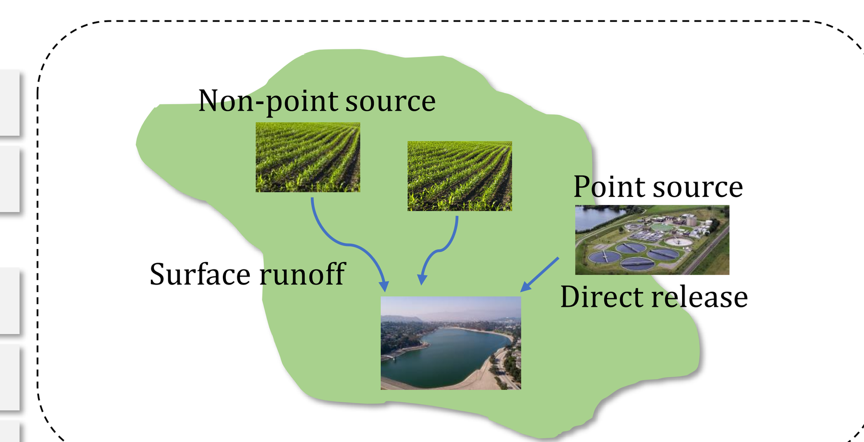
$$\mathrm{RSdif}_{expl,F} = \mathrm{FE}_{ws,F} \cdot \mathrm{WSdif}_E$$

$$\mathrm{FE}_{ws,F} = \mathrm{e}_F \cdot \mathrm{f}_F(\mathrm{R}_{nat})$$

$$\mathrm{WSdif}_E = \mathrm{WSdif}_{ant,E} + \mathrm{WSdif}_{nat,E}$$

$$\mathrm{WSdif}_{nat,E} = \mathrm{WSdif}_{fix,nat,E} + \mathrm{WSdif}_{dep,E}$$

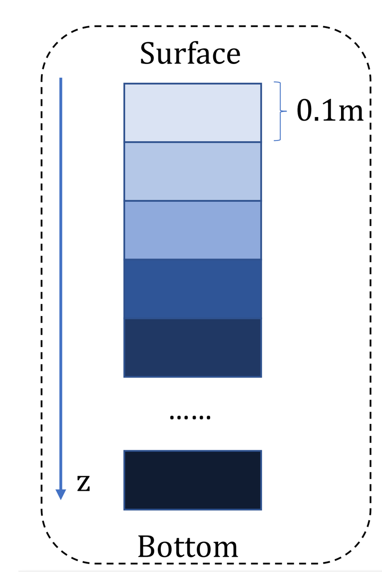
$$\mathrm{WSdif}_{ant,E} = \mathrm{WSdif}_{fe,E} + \mathrm{WSdif}_{ma,E} + \mathrm{WSdif}_{fix,ant,E} + \mathrm{WSdif}_{dep,ant,E} - \mathrm{WSdif}_{ex,E}$$



- **Point source** emission: calculate from population
- **Explicit non-point** source release: calculate from supply chain results
- **Inexplicit non-point source** release: calculate using equations with globally calibrated parameters
- **Nutrient entering waterbody** from non-point sources: calculate using equations with globally calibrated parameters and runoff volume (precipitation data)

Algae Growth Model

- **PROTECH Model**



$$\frac{\Delta X}{\Delta t} = r' \cdot X - S - G - D$$
$$r' = \min\{r'_{cor(\theta,I)}, r'_P, r'_N\}$$

X: concentration of Chl-a [mg/m^3]
r': growth rate [day^{-1}]
S: rate of loss due to settling out [$mg/m^3\ day^{-1}$]
G: rate of loss due to grazing [$mg/m^3\ day^{-1}$]
D: rate of loss due to dilution [$mg/m^3\ day^{-1}$]

Step 1: Determine base growth rate

$$r'_{20} = 1.142 \left(\frac{s}{v}\right)^{0.325} \quad [\mathrm{day}^{-1}]$$

Step 2: Consider temperature (θ)

$$\log(r'_\theta) = \log(r'_{20}) + b\left[\frac{1000}{273+20} - \frac{1000}{273+\theta}\right]$$
$$b = 3.378 - 2.505 \log\left(\frac{s}{v}\right)$$

Step 3: Consider photoperiod (T)

$$r'_{(\theta,I)} = \frac{r'_\theta \cdot T}{24} \quad \text{If: } z<h_p$$
$$r'_{(\theta,I)} = 0.223 \cdot \alpha_r I'_0 e^{-\varepsilon z} \quad \text{If: } z>h_p$$

Step 4: Consider respiration

$$r'_{cor(\theta,I)} = 1.055 \cdot r'_{(\theta,I)} - 0.07 \cdot r'_\theta$$

Step 5: Consider impact of nutrients

For each species, using the following mass ratio to calculate the nutrient demand:

$$\mathrm{N:P:Chl\text{-}a} = 8.3:1.2:1$$

If the overall demand is not satisfied, the rate for each species is discounted.

Step 6: Calculate grazing and dilution

$$\frac{\Delta G}{\Delta t} = 0.005 e^{0.22970} \quad \text{If } X_{ed} < 1.6\ mg/m^3$$
$$G = X_{ed}(1 - e^{-g}) \quad \text{If } X_{ed} > 1.6\ mg/m^3$$

Where g is related to temperature and chl-a conc.

$$w = \frac{Q}{V}$$
$$D = X(1 - e^{-w})$$

Step 8: Distribute algae in mixed layer

Step 9: Determine algae movement

Step 10: Update nutrient environment

Species	Light Condition	Movement
Chlorella	All	Sink 0.1m per day
Planktothrix	> 100 μmol photon $m^{-2} s^{-1}$	Sink 0.3 m per day
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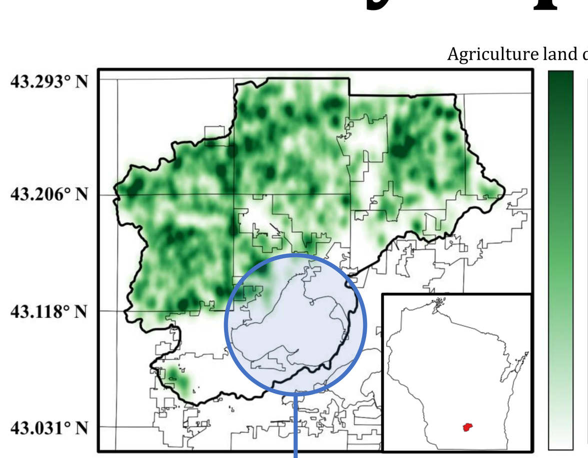
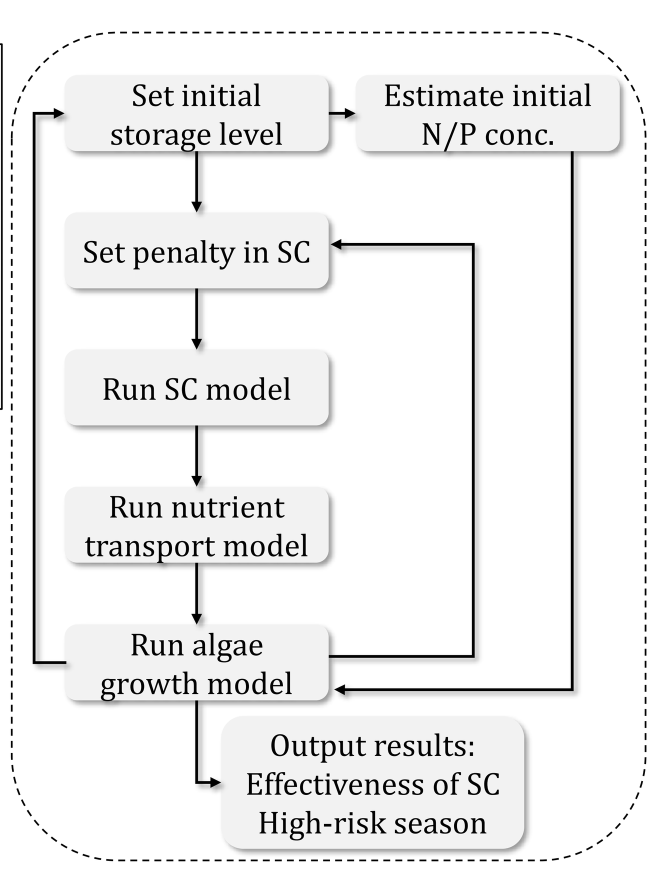
Case Study: Upper Yahara Watershed

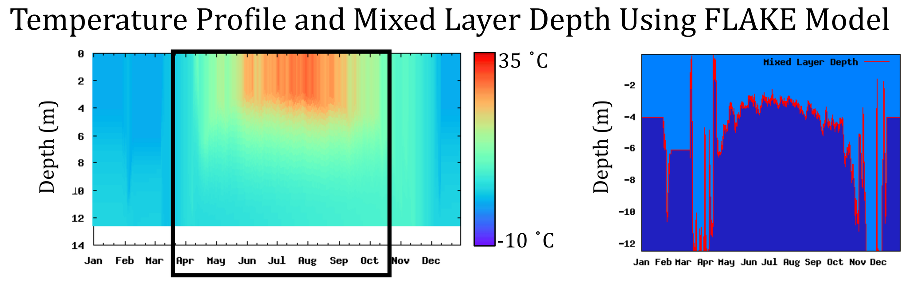


Nodes in supply chain:
- 55 beef farms
- 148 dairy farms
- 1167 land nodes
- 1 company (external)

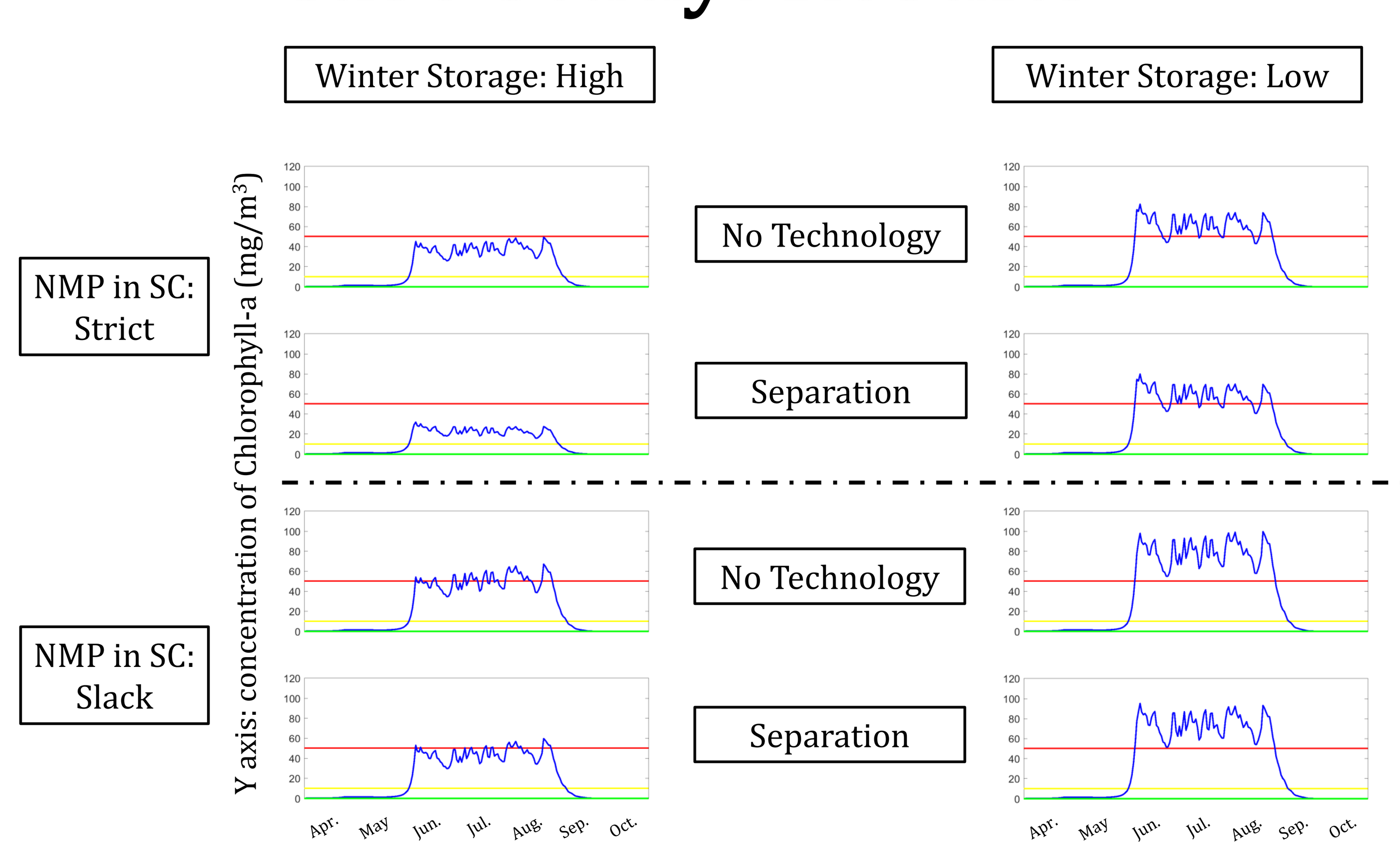
Lake Mendota in Madison, WI



Temperature Profile and Mixed Layer Depth Using FLAKE Model



Case Study: Results



Conclusions

- ☐ As normally known, we predict that HABs are more likely to occur in summer (Jun., Jul. and Aug.) in Lake Mendota, WI.
- ☐ Strategies in winter manure management can influence the algae growth in the next year: if manure is applied frequently in winter, either using strict NMP in the optimal supply chain or using technologies **cannot** prevent HABs.
- ☐ If most manure is stored during winter, when applying manure in summer, we **can** use strict NMP in supply chain and use technologies to produce products which are demanded by external customers to lower the nutrient release and finally prevent HABs.
- ☐ Future topics include: finer supply chain design (GIS data, elevation etc.) and nutrient transport (soil-hydrology simulation), increase the framework compatibility with more advanced tools (e.g. SWAT), computational study in solving large LP and MILP models, uncertainty analysis etc.

Acknowledgments

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Main References:

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