Logistics Network Management of Livestock Waste for Spatiotemporal Control of Nutrient Pollution in Water Bodies

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Abstract

Nutrient pollution is a widespread water quality problem, which originates from excess nutrient runoff from agricultural land, improperly managed farming operations, and point sources such as wastewater treatment plants. Some nutrient pollution impacts include harmful algal blooms (HABs), hypoxia, and eutrophication. HABs are major environmental events causing severe health threats and economic losses (e.g., tourism, real estate, commercial fishing). Excess nutrient flows exhibit complex spatiotemporal dynamics that span multiple scales and result from point source direct emissions, e.g., wastewater treatment plans, and from non-point sources such as the seasonal application of fertilizers (e.g., livestock manure) to agricultural lands, which are spatially dispersed and connected to water bodies through complex geospatial pathways. Interestingly, a dimension of the nutrient pollution problem that has not received as much attention is
how this interacts with organic waste management practices. This is important because the transport of nutrients to water bodies is a spatiotemporal phenomenon that involves multiple scales and that is tightly related to the spatial layout and geography of agricultural lands surrounding the water bodies, to the timing of nutrient source releases, and to regional nutrient imbalances. In this work, we show how the nutrient concentration in water bodies and other factors over time and space are related to HAB development and how logistics management of livestock waste (manure) can be used to conduct spatio-time control and prevention of nutrient pollution and associated impacts such as HAB events. Specifically, we show that waste logistics networks can be used to control HABs by strategically utilizing waste storage and processing systems and by enabling nutrient mobilization via waste transportation and processing. Our framework integrates spatiotemporal organic waste logistic management modeling, nutrient transport modeling, and HAB prediction modeling and spans multiple dimensions. We use a case study for dairy farms affecting the Upper Yahara watershed in the State of Wisconsin (U.S.) to illustrate the benefits of the proposed approach for understanding nutrient pollution and its impacts across space and time.

**Keywords:** logistics network, livestock waste, multiscale, nutrient pollution, algal blooms
Introduction

Anthropogenic nutrient pollution, primarily consisting of nitrogen and phosphorus, is one of the most widespread water quality problems facing the U.S., with far-ranging repercussions for environmental quality, human health, and economic success. Sources of nutrient pollution are classified as either non-point or point sources. Non-point sources include nutrient releases from agricultural land, natural land, and stormwater, while point sources include nutrient releases from permitted facilities such as wastewater treatment plants (WWTPs)\(^1\). Particularly, harmful algal blooms (HABs) represent a critical and challenging nutrient pollution impact. HABs pose severe health threats due to the release of toxins and the appearance of hypoxia in water bodies. In addition, HABs lead to significant economic losses since they impact tourism, recreational and commercial activities, and property values. For instance, HABs increase treatment costs for drinking water and impact industries that depend on fresh water (e.g., power plants).

Algal species generate significant levels of toxins that threaten human and aquatic life. Rapid algae growth is associated with subsequent decreases in dissolved oxygen content of the water body, resulting in widespread die-offs of aquatic life. HABs have economic impacts in the form of remediation costs for water treatment and reduction in real estate values of impacted areas. Specifically, algae create unpleasant odors and visual aesthetics that decrease the value of recreational water systems.\(^1,2\) In 2009, it was estimated that 30% of the lakes from 36 states in the U.S. have reported toxic cyanobacterial bloom issues.\(^3\) The U.S. Environmental Protection Agency (U.S. EPA) estimates that nutrient pollution and associated HABs lead to annual tourism losses of one billion dollars and to commercial fishing annual losses of tens of millions of dollars.\(^2\)

Multiple indicators have been proven to measure nutrient pollution and to estimate the risk and severity of HABs. One simple indicator is the concentration of nitrogen and phosphorus in a water body, which is used by many regulatory bodies for monitoring and con-

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\(^1\)https://www.epa.gov/nutrientpollution/sources-and-solutions
\(^2\)https://www.epa.gov/nutrientpollution/effects-economy
\(^3\)
trolling water quality. For example, the suggested phosphorus concentration for lake water in the State of Wisconsin is 15-40 mg P/m$^3$.\textsuperscript{4} In life cycle assessment (LCA) studies, the so-called eutrophication potential (EP) metric is usually calculated using nutrient release and fate factors.\textsuperscript{5,6} The EP metric is a suitable metric of the long-term impact of nutrient release but neglects short-term seasonal impacts. Diverse indicators have also been developed to directly measure the severeness of HABs such as the Secchi depth, algae cell density, concentration of chlorophyll-a (chl-a), and concentration of toxins (e.g., microcystins).\textsuperscript{7} Carlson\textsuperscript{8} proposed a comprehensive indicator, the trophic state index (TSI), which incorporates the Secchi depth, phosphorus concentration, and chl-a concentration. The TSI is used in water quality reports to classify the severity of eutrophication of a water body.\textsuperscript{9} Specifically, a water body is eutrophic when the TSI is larger than 50 and is hypereutrophic if the TSI is larger than 60.

Nutrient pollution and HAB issues have been widely studied from the perspectives of human health, economic analysis, prediction and monitoring, treatment, and remediation.\textsuperscript{10-13} Interestingly, a dimension of the nutrient pollution problem that has not received as much attention is how this interacts with \textit{agricultural logistics network management practices}. This is important because the transport of nutrients to water bodies is a spatiotemporal phenomenon that involves multiple scales and that is tightly related to the spatial layout and geography of agricultural lands surrounding the water bodies, to the timing of nutrient source application, and to regional nutrient imbalances. Specifically, by designing an appropriate logistics network that stores, mobilizes, and processes organic waste, it is possible to balance and recycle nutrients more effectively and with this control the timing and location of nutrient runoff to water bodies. The value of logistics network management on the mitigation of environmental impacts of livestock waste has been previously analyzed from the perspective of air quality (air emissions and energy efficiency) but not from the perspective of water quality.\textsuperscript{14} Some recent studies have focused on the prediction of nutrient pollution and HABs by using statistical modeling and machine learning techniques.\textsuperscript{15,16} Such studies consider diverse factors that affect HAB development such as geography and in-excess
nutrient flows but do not offer alternatives into how to influence and control such flows.

In this work, we analyze how logistics networks can be used to enable spatiotemporal control of in-excess nutrient flows and associated HABs. To do so, we propose a computational framework that incorporates a logistics network model that seeks to identify optimal locations for waste storage and processing technologies as well as optimal strategies for mobilization of waste and derived products in a given region.\textsuperscript{17,18} In addition, the framework incorporates a medium-fidelity nutrient transport model which captures dynamics of the transport process from agriculture lands to water bodies. Moreover, the framework incorporates an algae bloom prediction model that tracks the nutrient concentration of a water body over time and relates this to the algae bloom level. The framework integrates these models to design a four-dimensional model for organic waste management that simultaneously mitigates investment, transportation, operational, and environmental costs. We present a series of case studies in the Upper Yahara watershed in the State of Wisconsin to illustrate the practicability of the framework.

**Computational Framework**

In this section, we introduce a computational framework to connect the logistics network, nutrient transport, and HABs prediction models. The structure of the framework is summarized in Figure 1. First, data regarding geographical locations, market information, technology information, etc. are fed into the logistics network model, which can then output the decision-making information (e.g. transportation routes, technology arrangement) together with net nutrient releases at each location. Then, the non-point release data obtained from the logistics network model and the point source data are imported into the nutrient fate and transport model to estimate the nutrient amount that reaches the water body. In the third step, the HAB simulation model will take outputs from previous models and data about weather and the water body to simulate the trend and distribution (over depth) of the concentration of chl-a. The results can then provide feedback information to the logistics
network design procedure and adjustments can be made when solving the logistics network model. These models are solved recursively until the HAB levels are satisfactory or until the model finds the logistics network alone cannot eliminate HAB threats given the spatial and temporal scope of uncontrolled externalities (weather, uncontrolled nutrient release, etc.).

**Algae Growth Model**

Algae growth in a water body depends on seasonal dynamic factors such as water temperature, sunlight, and nutrient concentration. Therefore, steady-state modeling or models with annual time resolutions are not adequate. For example, nutrient release at a given time may not cause HABs immediately but may contribute significantly at a later point in time when other seasonal factors become more favorable (e.g., application of manure in cold months leads to nutrients accumulation in the soil, which in turn will raise the probability of HABs in the spring when nutrients runoff with melted snow). Therefore, *long-term* proactive management actions must be taken in advance, but determining a suitable lead time is non-trivial.

The PROTECH (Phytoplankton RespOnses To Environmental CHange) algae growth model was used. We briefly review the key features of this model. Further details can be found in the original publications.\textsuperscript{19,20} The PROTECH model uses the concentration of chlorophyll-a (chl-a) as an indicator of the algae formation and simulates the algae growth at different depths of the water body and at various times. PROTECH is a one-dimensional spatial model (vertical dimension) and ignores the horizontal gradients of nutrient concentration, temperature, and other physical properties of the lake or recipient water body where the HABs may occur. Furthermore, it assumes that the nutrient concentration is uniform throughout the water body.

The daily change in the concentration of chl-a is given by equation (1), where $X$ represents the concentration of chl-a [mg/m$^3$], $r'$ represents the growth rate [day$^{-1}$], and $G$, $S$, and $D$ represent the rate of decrease in the concentration of chl-a due to animal grazing,
Figure 1: Structure of the proposed computational framework
settling out of the region because of algae movement, and dilution [mg/(m\(^3\)·day)].

\[
\frac{\Delta X}{\Delta t} = (r' \cdot X) - G - S - D
\]  

(1)

The growth rate \(r'\) is determined by equation (2), where \(r'_{\text{cor}(\theta,I)}\) is the growth rate determined by the temperature and photoperiod conditions (i.e, the physiological reaction of algae to the length of day), \(r'_P\) is the growth rate determined by the phosphorus supply, and \(r'_N\) is the growth rate determined by the nitrogen supply. In the original model, silicon is also considered as a limiting nutrient for diatoms, but in this work, we ignore the impact of silicon because diatoms typically cause HABs only in marine water.

\[
r' = \min \{r'_{\text{cor}(\theta,I)}, r'_P, r'_N\}
\]  

(2)

To determine \(r'_{\text{cor}(\theta,I)}\), an ideal growth rate at 20\(^\circ\)C needs to be determined first using equation (3), where \(s\) and \(v\) are the average surface area [\(\mu m^2\)] and volume [\(\mu m^3\)] of an algae cell. This equation represents the relationship between unlimited growth rate at 20\(^\circ\)C and the size of an algae cell. Then, the influence of temperature is considered using equation (4), where \(r'_\theta\) is the ideal growth rate at temperature \(\theta\) [\(^\circ\)C], and \(b\) is an algae species related constant (equation (5)) obtained using the geometry of the algae cells.

\[
r'_{20} = 1.142 \left(\frac{s}{v}\right)^{0.325}
\]  

(3)

\[
\log(r'_\theta) = \log(r'_{20}) + b \cdot \left[\frac{1000}{273 + 20} - \frac{1000}{273 + \theta}\right]
\]  

(4)

\[
b = 3.378 - 2.505 \log\left(\frac{s}{v}\right)
\]  

(5)

The influence of light conditions is critical in the development of HABs. We use equation (6) to calculate the photon flux \(I_k\) [mol/(m\(^2\)·s)] necessary to saturate the growth rate at temperature \(\theta\), where \(\alpha_r\) is also an algae species related constant (equation (7), where \(m\) is the maximum cell dimension of an algae species [\(\mu m\)]). The light compensation depth \(h_p\) [m]
is calculated using equation (8) (if the algae is in a deeper position then the growth rate is limited by the light), where $I_0$ is the photon flux at the water surface (which can be obtained using the weather information like clearness), and $\epsilon$ [m$^{-1}$] is the vertical light extinction coefficient. We use equation (9) to determine $r'_{(\theta,I)}$, the growth rate limited by temperature and light conditions, where $z$ [m] is the depth where the algae cell is located. For cells above the light compensate depth ($z \leq h_p$), we only discount the temperature limited rate $r'_\theta$ by the length of daytime $T$ [hour]; while for cells below ($z > h_p$), the rate decreases exponentially. Finally, to determine the value of $r'_{cor(\theta,I)}$, the respiration effect needs to be corrected using equation (10).

\begin{align*}
I_k &= \frac{r'_\theta}{\alpha_r \cdot 3600 \cdot 24} \quad (6) \\
\alpha_r &= 0.257 \cdot \left( \frac{m \cdot s}{v} \right)^{0.236} \quad (7) \\
h_p &= \frac{1}{\epsilon} \ln \left( \frac{2 \cdot I_0}{I_k} \right) \quad (8) \\
r'_{(\theta,I)} &= \begin{cases} 
\frac{r'_\theta \cdot T}{24}, & z \leq h_p \\
0.223 \cdot 3600 \cdot 24 \cdot \alpha_r \cdot I_0 \cdot e^{-\epsilon z}, & z > h_p
\end{cases} \quad (9) \\
r'_{cor(\theta,I)} &= 1.055 \cdot r'_{(\theta,I)} - 0.07 \cdot r'_\theta \quad (10)
\end{align*}

The nutrient limiting rates $r'_P$ and $r'_N$ are calculated based on the assumption that the algae mass composition follows a concentration ratio of N : P : chl-a equal to 8.3 : 1.2 : 1.\textsuperscript{21} We first calculate the total demand of N and P based on the growth rate $r'_{cor(\theta,I)}$. If the nutrient supply in the water body is sufficient (larger than the nutrient demand), then we set the nutrient limiting rate ($r'_P$ or $r'_N$) to infinity since the nutrient is not limiting the growth of algae; otherwise, we set the nutrient limiting rate as the product of $r'_{cor(\theta,I)}$ and the ratio of nutrient supply and demand (which is less than 1).

For the rate of decrease in concentration of chl-a, the grazing rate is computed based on current chl-a concentration and temperature, the settling rate is determined by the depth of the mixed layer of the lake, the light profile in the lake, and the corresponding algae
movement actions and the dilution rate is calculated based on the inflow volume and the lake volume. After calculating the chl-a concentration change using equation (1), we update the nutrient concentration in the water body using equation (11) and (12), where \( P_t \) and \( N_t \) are the phosphorus and nitrogen concentration [mg/m\(^3\)] in the water body at time \( t \) [day], \( V \) is the volume of the lake [m\(^3\)], \( w \) is the dilution ratio (the ratio of total daily volume inflow and \( V \)), and \( P_{in,t} \) and \( N_{in,t} \) are the inflow phosphorus and nitrogen [mg] at time \( t \), which is obtained from the nutrient transport model (described next).

\[
P_{t+1} = \frac{1}{V} \left[ V \cdot \left( P_t \cdot e^{-w} - 1.2 \cdot \Delta X \right) + P_{in,t} \right] \quad (11)
\]

\[
N_{t+1} = \frac{1}{V} \left[ V \cdot \left( N_t \cdot e^{-w} - 8.3 \cdot \Delta X \right) + N_{in,t} \right] \quad (12)
\]

**Nutrient Transport Model**

A nutrient transport model is used to capture the dynamics of nutrient release from point sources (e.g., WWTPs) and non-point sources (e.g., agricultural lands) to the water bodies. Nutrient emissions from WWTPs directly enter the water body while nutrients from non-point sources result from the spreading of fertilizer and animal manure on croplands, and other natural processes such as deposition fixation of gaseous nitrogen, and weathering of rocks. These nutrients reach the water bodies through the soil, surface runoff, and groundwater.

There are many models and tools available to study nutrient transport process.\(^{22}\) Some of these are based on the simulation of soil/hydrology, such as SWAT (Soil and Water Assessment Tool) and EPIC (Environmental Policy Integrated Climate).\(^{23}\) The results from these models are more accurate, but they usually require more input data on the soil conditions and of the hydrological system in the study region. To reduce the need for input data and the computational burden, a less-complex nutrient transport model is required. In this work, we use a watershed model called NEWS2 (Nutrient Export from WaterSheds 2). Here we provide a brief review of the model structure. Model details can be found in.\(^{24}\) The components
of this model are illustrated in Figure 2.

**Figure 2:** Sketch of nutrient transport NEWS2 model

The NEWS2 model predicts the total nutrient that exits a watershed (enters a water body) \( (\text{Yield}_E) \) directly from point sources \( (\text{RS}^{\text{pnt}}_E) \) and non-point sources \( (\text{RS}^{\text{dif}}_E) \), as described by equation (13). The subscript \( E \) indicates the type of the nutrient, which can be either nitrogen (N) or phosphorus (P).

\[
\text{Yield}_E = \text{RS}^{\text{pnt}}_E + \text{RS}^{\text{dif}}_E, \ E \in \{N, P\} \tag{13}
\]

The contribution of point sources is estimated from the human population \( (I) \) within the study region and the fraction of nutrients removed by the WWTPs \( (\text{hw}_{\text{frem}, E}) \) are described by equation (14), where \( W_{\text{Shw}, E} \) is the amount of nutrient \( E \) in human waste.

\[
\text{RS}^{\text{pnt}}_E = (1 - \text{hw}_{\text{frem}, E}) \cdot I \cdot W_{\text{Shw}, E}, \ E \in \{N, P\} \tag{14}
\]

The non-point sources are divided into an explicit component \( (\text{RS}^{\text{dif, expl}}_E) \) and a non-explicit component \( (\text{RS}^{\text{dif, ec}}_E) \) (equation (15)). The non-explicit component is computed using globally calibrated parameters \( (\text{EC}_F) \) and surface runoff \( (R_{\text{nat}}) \), seen in equation (16). The subscript \( F \) indicates the form of the nutrient, which can be either organic (O) or inorganic (I). The function \( f_F \) is defined in equation (17), where \( a_F \) and \( b_F \) are also globally calibrated parameters.

\[
\text{RS}^{\text{dif}}_E = \text{RS}^{\text{dif, expl}}_E + \text{RS}^{\text{dif, ec}}_E, \ E \in \{N, P\} \tag{15}
\]
\[
R\text{Sdif}_{\text{EC},E} = \sum_{F \in \{\text{IE,OE}\}} f_F(R_{\text{nat}}) \cdot \text{EC}_F, \ E \in \{\text{N,P}\}
\] (16)

\[
f_F(R_{\text{nat}}) = \begin{cases} 
1 + \left(\frac{R_{\text{nat}}}{a_F}\right)^{-\text{by}_F}^{-1}, & F = \text{IP} \\
\text{OI}, & F = \text{IN, ON, OP}
\end{cases}
\] (17)

The explicit component includes nutrients release from natural lands (WSdif_{\text{nat},E}) such as wetlands, and anthropogenic lands (WSdif_{\text{ant},E}) such as agriculture lands. For both terms, a nutrient balance is conducted based on nutrient input including fertilizer (WSdif_{\text{fe},E}), animal waste (WSdif_{\text{ma},E}), fixation (WSdif_{\text{fix,nat},E} and WSDif_{\text{fix,ant},E}), and deposition (WSdif_{\text{dep,nat},E} and WSDif_{\text{dep,ant},E}), and nutrient output (animal grazing and plant removal, WSDif_{\text{ex},E}), as described by equation (19) and (20)). The variables in the nutrient balance equations are either obtained from the logistics network model (highlighted in boldface) or directly from data.

\[
\text{WSdif}_E = \text{WSdif}_{\text{nat},E} + \text{WSdif}_{\text{ant},E}; \ E \in \{\text{N,P}\}
\] (18)

\[
\text{WSdif}_{\text{nat},E} = \text{WSdif}_{\text{fix,nat},E} + \text{WSdif}_{\text{dep,nat},E}; \ E \in \{\text{N,P}\}
\] (19)

\[
\text{WSdif}_{\text{ant},E} = \text{WSdif}_{\text{fe},E} + \text{WSdif}_{\text{ma},E} + \text{WSdif}_{\text{fix,ant},E} + \text{WSdif}_{\text{dep,ant},E} - \text{WSdif}_{\text{ex},E}; \ E \in \{\text{N,P}\}
\] (20)

A watershed export coefficient (FE_{ws,F}) is used to calculate the fraction of nutrients that finally enters the water body. This parameter is estimated using the surface runoff and globally calibrated parameters (\(e_F\)), as described by equation (21) and (22). The surface runoff \(R_{\text{nat}} \text{ [m]}\) is related to precipitation using a standard curve number method (equation (23)-(24)),\(^25\) where \(t\) is one day in the time scope considered (e.g. for annual calculation \(t = 1, 2, \ldots, 365\)), \(\text{PR}_t\) is the daily precipitation [mm], \(S_t\) is the daily rainfall retention parameter [mm], and \(\text{CN}_t\) is the curve number for day \(t\).

\[
\text{FE}_{ws,F} = e_F \cdot f_F(R_{\text{nat}}), \ F \in \{\text{IN, ON, IP, OP}\}
\] (21)
\[ ES_{\text{dif},E} = \sum_{F \in \{IE,OE\}} FE_{ws, F} \cdot WS_{dif} E, \quad E \in \{N, P\} \] (22)

\[ R_{\text{nat}} = \sum_{t} \frac{(PR_t - 0.2S_t)^2}{PR_t + 0.8S_t} \times \frac{1}{1000} \] (23)

\[ S_t = 25.4 \times \left( \frac{1000}{CN_t} - 10 \right) \] (24)

Some simplifying assumptions were made in order to make the NEWS2 model more compatible with our framework. NEWS2 is used to calculate the annual nutrient output from a watershed and therefore we assume that a biweekly output can be calculated using the same model and parameters given finer input data. However, the transport delay in the soil and the river should be considered using equation (25)-(27), where \( R_{g,t} \) is the generated runoff at day \( t \) [mm], \( R_t \) is the runoff entering water body at day \( t \) [mm], \( R_{stor,t} \) is the stored runoff within the watershed in day \( t \) [mm], \( \text{surlag} \) is the surface runoff lag coefficient [day], \( t_c \) is the time of concentration [days]. In addition, the NEWS2 model is typically used for large river basins (e.g., Mississippi River Basin). In our case study, we assume that a smaller watershed can also fit into this model when using global parameters. Although these assumptions may lead to lower accuracy, they still capture the basic features needed for our analysis.

\[ R_{g,t} = \frac{(PR_t - 0.2S_t)^2}{PR_t - 0.8S_t} \] (25)

\[ R_t = (R_{g,t} + R_{stor,t-1}) \times \left( 1 - \exp^{-\frac{\text{surlag}}{t_c}} \right) \] (26)

\[ R_{stor,t} = R_{stor,t-1} + R_{g,t} - R_t \] (27)

After the modification, the model can calculate the nutrient release \( \text{Yield}_{E,\tau} \) at a smaller time scope \( \tau \). We use a simple approximation method that assumes the daily nutrient inflow is proportional to the ratio of daily runoff and the total runoff in \( \tau \). This leads to the following
equations that connect the Yield\(_{E,\tau}\) and \(P_{in,t}\) \(N_{in,t}\) in the algae growth model.

\[
P_{in,t} = \text{Yield}_{P,\tau} \times \sum_{t \in \tau} R_t, \quad N_{in,t} = \text{Yield}_{N,\tau} \times \sum_{t \in \tau} R_t
\]  

(28)

**Logistics Network Model**

In this section, we introduce the logistics network model for organic waste management used in this framework. We extend the logistics network model used in\(^{17,18}\) by incorporating a temporal dimension. This allows us to capture the impact of waste storage, crop growth, seasonality, and nutrient transport dynamics. The logistics network structure is shown in Figure 3. We use \(\mathcal{N}\) to represent the set of geographical (spatial) nodes (e.g., farms and agriculture lands), \(\mathcal{N}'\) to represent the set of geographical nodes excluding external customers, \(\mathcal{P}\) to represent the set of materials exchanged and transformed (e.g., raw manure and solid manure), \(\mathcal{S}\) to represent the set of time periods, and \(\mathcal{T}\) to represent the set of processing technologies (e.g., solid-liquid separation, granulation). All variables and parameters are defined in the nomenclature section.

**Material Balance and Conversion** Equation (29) captures the material balances at each spatial node and at each time step. The left-hand side contains the storage amount from previous time period \(I_{i,p,\tau-1}\), supply amount \(s_{i,p,\tau}\), total inflow \(\sum_{j \in \mathcal{N}} f_{j,i,p,\tau}\), and generation amount \(\sum_{t \in \mathcal{T}} g_{i,t,p,\tau}\). We note that, for the generation term, a positive value represents production and a negative value represents consumption. The right-hand side contains the storage amount in this time period \(I_{i,p,\tau}\), demand amount (consumption) \(d_{i,p,\tau}\), and total outflow \(\sum_{j \in \mathcal{N}} f_{i,j,p,\tau}\).

\[
I_{i,p,\tau-1} + s_{i,p,\tau} + \sum_{j \in \mathcal{N}} f_{j,i,p,\tau} + \sum_{t \in \mathcal{T}} g_{i,t,p,\tau} = I_{i,p,\tau} + d_{i,p,\tau} + \sum_{j \in \mathcal{N}} f_{i,j,p,\tau}, \quad (i, p, \tau) \in \mathcal{N} \times \mathcal{P} \times \mathcal{S}
\]  

(29)

Equation (30) captures material transformation through technologies. The generation term of each material \(g_{i,t,p,\tau}\) is calculated using the generation term of reference material
Figure 3: High-level logistics network structure

for the specific technology $g_{i,t,p,ref(t),\tau}$ and the relationship between the yield factors $\alpha_{t,p}$. For example, if a technology $t'$ has a reference material $p'$ with yield factor $\alpha_{t',p'} = -1$ and consumption amount $g_{i',t',p',\tau'} = -1,000$ at node $i'$ and time $\tau'$, then for a material $p*$ with yield $\alpha_{t',p*} = 0.1$, the corresponding generated amount of material $p*$ is $g_{i',t',p*,\tau'} = 100$.

$$g_{i,t,p,\tau} = \frac{\alpha_{t,p}}{\alpha_{t,ref(t)}} g_{i,t,p,ref(t),\tau}, \quad (i,t,p,\tau) \in \mathcal{N} \times \mathcal{T} \times \mathcal{P} \times \mathcal{S}$$  

(30)

**Capacity Constraints**  We use equation (31)-(33) to capture bounds for the demands, storage, and generation due to customers demand capacity, storage capacity, and technology capacity. The binary variables $x_{i,p}$ and $y_{i,t}$ are used to indicate the installation of storage systems and technologies at a special spatial location, respectively. In practice, many farms are already equipped with storage systems and some basic technologies like a screw press. Therefore, we can fix a part or all binary variables $x_{i,p}$ and $y_{i,t}$ when solving realistic problems. We note that because we define the reference material of technology as the main raw material, the corresponding generation term is always non-positive (because the raw mate-
rial is consumed), as indicated in equation (33).

\[ 0 \leq d_{i,p,\tau} \leq \bar{d}_{i,p,\tau}, \quad (i,p,\tau) \in \mathcal{N} \times \mathcal{P} \times \mathcal{S} \]  

\[ 0 \leq I_{i,p,\tau} \leq x_{i,p} \bar{I}_{i,p}, \quad (i,p,\tau) \in \mathcal{N} \times \mathcal{P} \times \mathcal{S} \]  

\[ -y_{i,t}C_t \leq g_{i,t,p_{ref(t)},\tau} \leq 0, \quad (i,t,\tau) \in \mathcal{N} \times \mathcal{T} \times \mathcal{S} \]  

We also impose bounds on the flow variables to satisfy transportation capacity, as shown in equation (34).

\[ 0 \leq f_{i,j,p,\tau} \leq \bar{f}_{i,j,p,\tau}, \quad (i,j,p,\tau) \in \mathcal{N} \times \mathcal{N} \times \mathcal{P} \times \mathcal{S} \]  

**Nutrient Balance**  Equation (35) and (36) capture phosphorus and nitrogen balances at each node and in each time period and help model nutrient management plans (NMPs). The net nutrient release \( NP_{i,\tau} \) (phosphorus) and \( NN_{i,\tau} \) (nitrogen) are calculated using the fertilizer supplement amounts \( ferP_{i,\tau} \) and \( ferN_{i,\tau} \), organic waste release amount (which is calculated using a nutrient content coefficient \( e_{P,p} \) and \( e_{N,p} \) and demand \( d_{i,p,\tau} \)), and the crop needs for phosphorous and nitrogen respectively (\( Pd_{i,\tau} \) and \( Nd_{i,\tau} \)). The net nutrition release is forced to be non-negative to ensure the growth of crops. We note that here we use a simple NMP model, in which only nutrient inputs and outputs are considered. In more advanced NMP models the nutrient goal is set by accounting for more factors such as results from a soil test and optimal nutrient requirements for different crops.

\[ NP_{i,\tau} = ferP_{i,\tau} + \sum_{p \in \mathcal{P}} e_{P,p} d_{i,p,\tau} - Pd_{i,\tau} \geq 0, \quad (i,\tau) \in \mathcal{N} \times \mathcal{S} \]  

\[ NN_{i,\tau} = ferN_{i,\tau} + \sum_{p \in \mathcal{P}} e_{N,p} d_{i,p,\tau} - Nd_{i,\tau} \geq 0, \quad (i,\tau) \in \mathcal{N} \times \mathcal{S} \]  

\[ ferP_{i,\tau}, ferN_{i,\tau} \geq 0, \quad (i,\tau) \in \mathcal{N} \times \mathcal{S} \]

After solving the logistics network model, nutrients from fertilizers, nutrients from animal waste, and nutrients taken by crops are communicated to the nutrient transport model.
using the following relationships.

\[ \text{WSdif}_{fe,N} = \sum_{i \in N'} \text{fer}N_{i,\tau}, \quad \text{WSdif}_{fe,P} = \sum_{i \in N'} \text{fer}P_{i,\tau} \]

\[ \text{WSdif}_{ma,N} = \sum_{i \in N'} \sum_{p \in P} e_{N,p}d_{i,p,\tau}, \quad \text{WSdif}_{ma,P} = \sum_{i \in N'} \sum_{p \in P} e_{P,p}d_{i,p,\tau} \]

\[ \text{WSdif}_{ex,N} = \sum_{i \in N'} Nd_{i,\tau}, \quad \text{WSdif}_{ex,P} = \sum_{i \in N'} Pd_{i,\tau} \]

**Economic Metrics**  
We use equation (37)-(40) to calculate the investment cost \( C_{\text{inv}} \) for any new installed technologies and storage systems, transportation cost \( C_{\text{trans}, \tau} \) for material movement, operational cost \( C_{\text{op}, \tau} \) for technologies, fertilizer cost \( C_{\text{fer}, \tau} \) to support crop growth when there is a nutrient deficiency, and supply cost \( C_{\text{sup}, \tau} \) for organic waste. The investment cost is calculated using the binary variables \( x_{i,p} \) and \( y_{i,t} \). In equation (37), \( \beta \) and \( \gamma \) are depreciation factors that capture the entire life of the technologies, \( C_{\text{inv},t} \) is the investment cost for technology \( t \), and \( C_{\text{inv},p} \) is the investment cost for a storage system with material \( p \). The transportation cost is calculated using the transportation flow \( f_{i,j,p,\tau} \), the distance between nodes \( D_{i,j} \), and the cost per unit flow per unit distance \( C_{\text{trans},p} \). The operational cost is calculated using the consumption amount of the raw material in each technology \( g_{i,t,p}c_{t}(t) \), and the unit operational cost \( C_{\text{op},t} \) for technology \( t \). We note that the \( C_{\text{op},t} \) is a comprehensive number that counts different aspects such as utility and labor. The fertilizer cost is calculated using the amount of used fertilizer and the break-down market prices of the nitrogen and phosphorus in the fertilizers \( (\rho^P \text{ and } \rho^N) \), respectively. We note that the fertilizer costs are calculated under different assumptions; for instance, when one fertilizer contains N and P simultaneously or when the farmer decides to satisfy nitrogen need only. The supply cost and revenue are calculated using equation (41) and (42) by taking the product of supply and demand values with their corresponding prices \( (\rho_{s,i,p,\tau} \text{ and } \rho_{d,i,p,\tau}) \).

\[
C_{\text{inv}} = \beta \sum_{i \in N} \sum_{t \in T} y_{i,t} C_{\text{inv},t} + \gamma \sum_{i \in N} \sum_{p \in P} x_{i,p} C_{\text{inv},p}
\]  

(37)
\begin{align*}
C_{\text{trans},\tau} &= \sum_{i \in N} \sum_{j \in N} \sum_{p \in P} f_{i,j,p,\tau} D_{i,j} C_{\text{trans},p}, \quad \tau \in S \\
C_{\text{op},\tau} &= \sum_{i \in N} \sum_{t \in T} -g_{i,t,p_{r(t)},\tau} C_{\text{op},t}, \quad \tau \in S \\
C_{\text{fer},\tau} &= \sum_{i \in N'} \rho_{P_{\text{fer}}P} i,\tau + \sum_{i \in N'} \rho_{N_{\text{fer}}N} i,\tau, \quad \tau \in S \\
C_{\text{sup},\tau} &= \sum_{i \in N} \sum_{p \in P} s_{i,p,\tau} \rho_{s_{i,p,\tau}}, \quad \tau \in S \\
R_{\tau} &= \sum_{i \in N} \sum_{p \in P} d_{i,p,\tau} \rho_{d_{i,p,\tau}}, \quad \tau \in S
\end{align*}

Objective Function

The logistics network design problem is a conflict resolution (multi-objective) problem that seeks to trade-off multiple economic and environmental metrics (e.g., profit and nutrient pollution) that affect diverse stakeholders. In this work, we consider cost, revenue, and nutrient released to the environment:

\[
\min \{C_{\text{inv}}, C_{\text{trans},\tau}, C_{\text{op},\tau}, C_{\text{fer},\tau}, C_{\text{sup},\tau}, -R_{\tau}, NP_{i,\tau}, NN_{i,\tau}\}
\]

To solve this optimization problem, we use a collective function to represent the social preference by assuming that all stakeholders cooperate to achieve a common goal. The solution obtained under this approach contrasts with that obtained in a competitive market setting, in which every stakeholder maximizes its own individual objective.

In equation (44), \(\lambda^P\) and \(\lambda^N\) represent the per unit environmental costs of excess phosphorus and nitrogen. High values of the environmental cost represent a strict policy where non-compliance with the NMPs will result in a high economic penalty, while low values represent more forgiving (loose) policy. For simplicity, we assume that the environmental costs are uniform throughout the study region and do not change over time.

\[
\min \left( C_{\text{inv}} + \sum_{\tau \in S} (C_{\text{trans},\tau} + C_{\text{op},\tau} + C_{\text{fer},\tau} + C_{\text{sup},\tau} - R_{\tau}) + \lambda^P \sum_{i \in N'} \sum_{\tau \in S} NP_{i,\tau} + \lambda^N \sum_{i \in N'} \sum_{\tau \in S} NN_{i,\tau} \right)
\]
Case Study

In this section, we demonstrate the applicability of the proposed framework by considering a case study in the State of Wisconsin (WI).

Study Region

We choose the Upper Yahara Watershed (Lake Mendota basin) as the study region. The map in Figure 4 shows the geographical location and boundary of the study region and the density of agriculture lands (farms and cropland) in the region.

![Map of Upper Yahara Watershed](image)

**Figure 4:** Agricultural land density in Upper Yahara watershed region in Wisconsin

The study region is currently affected by significant nutrient pollution due to high-intensity agricultural activities. We define the nutrient balance index (NBI) as the ratio of nutrient applied to land to the amount of nutrient that is removed by crops. This implies that when NBI is greater than one, the nutrient will accumulate in the region and potentially create nutrient pollution issues while, when NBI is less than one, it indicates that there is a nutrient deficiency in the soil (overall soil fertility may be declining and therefore is not sustainable in the
long-run). The NBI value for phosphorus in the Upper Yahara Watershed in the year 2012 and 2013, was estimated to be 1.95 and 1.35, respectively.\textsuperscript{26} We estimate that the NBI value for the year 2017 was 1.46 based on crop planting, nutrient removal by those crops, and the nutrients added to the land in the form of animal waste. Exact values of such imbalance are difficult to ascertain due to the inherent uncertainty in crop yield values and manure composition.\textsuperscript{27} In addition, according to the statistics from the U.S. Decennial Census, the population in the City of Madison has increased since the 1990s at a rate of 10\% per decade. The increasing population causes more intense human activity and the generation of more organic waste. As a result, it is anticipated that nutrient accumulation in the study region will persist in recent years.

The excess nutrients in the study region impact water quality. The Wisconsin Department of Natural Resources has reported that the TSI value for Lake Mendota has been fluctuating between 50 and 60 since the 1980s\textsuperscript{3}, indicating that the lake is eutrophic and at an increased risk of suffering from HABs. The UW-Madison Center for Limnology also publishes frequent updates of HAB events in Lake Mendota \textsuperscript{4}.

**Model Settings and Data Collection**

The computational framework requires significant and different types of data. In this section, we discuss the settings and data input for each model. The data flow of the modeling framework is presented in Figure 5. The data and code are available at https://github.com/zavalab/JuliaBox/tree/master/SC_HABs.

**Setting and Data for Logistics Network Model.** The logistics network model as described in Figure 5(a) requires significant input data corresponding to node locations, supply values of organic waste, demand values of derived products, crops within the study area, storage systems, and technologies. In our study, we consider 1,371 nodes, which include 55 beef

\textsuperscript{3}https://dnr.wi.gov/
\textsuperscript{4}https://limnology.wisc.edu/
Figure 5: Data flow of the modeling framework (red boxes are linking variables)
farms, 148 dairy farms, 1167 agriculture lands, and an external customer located outside the study region that is used to help balance the region (e.g., this can be a set of companies requesting solid manure as fertilizer). To reduce computational complexity, we assume that agriculture lands within 5 km belong to the same management organization, which reduces the 1,167 agriculture lands to 88 nodes. Farms supply cow manure, beef manure, and heifer manure. The supply amount is estimated based on the number of animals at each farm.\textsuperscript{28,29} We assume that waste production is uniformly distributed throughout the year.\textsuperscript{30} The time step in the model is set to two weeks. At a particular point in time, animal waste can be sent to agricultural lands, to a storage system, or to separation (processing) technologies to produce solid and liquid manure fractions. We use existing data for storage systems and fix the associated binary variables.\textsuperscript{29} Yield factors, the separation efficiency of nutrients, investment and operational costs are obtained from previous studies.\textsuperscript{31} We also assume that only those farms with more than 500 animal units are equipped with separation technologies. The liquid and solid fraction of manure can be used for land application separately, and the solid fraction can also be sold to the external customer.

The nutrient demand at agriculture lands is calculated using crop types reported in 2017, the land area, and the nutrient removal rate provided by USDA’s crop nutrient tool (which automates and incorporates information in the Agricultural Waste Management Field Handbook\textsuperscript{32}). Based on the nutrient uptake curves of several crops (corn, wheat),\textsuperscript{33} we observe that nutrient accumulation in the crops is almost linear to time. Therefore, we assume that nutrient demand is distributed evenly during the growing season. The growing time for different crops is obtained from Agricultural Handbook provided by the National Agricultural Statistics Service of the United States Department of Agriculture.\textsuperscript{34} For the legumes (such as the soybean plant) the nitrogen demand is zero because of their capability of nitrogen fixation. The logistics network models solved in our studies are large-scale linear programming problems. The models were formulated using the Julia-based modeling framework JuMP and were solved with Gurobi (Version 7.5.2). The model instances solved are computationally challenging. The largest model contains 360,935 linear constraints and over
Setting and Data for Nutrient Transport Model. The nutrient transport model requires also significant input data corresponding to the nutrient release from point and non-point sources, and the average precipitation within the study area, as shown in Figure 5(b). For point-source release, we observe that there is no effluent directly to the Lake Mendota from WWTPs according to the Madison Metropolitan Sewerage District. Nutrient release corresponding to the non-point sources, specifically the agricultural sector (fertilizer, animal waste, and crop uptake), is extracted from the results of the logistics network model as explained in the previous Section. For the nutrient fixation data, we use global parameters reported by Bouwman et al. Specifically, the P fixation and deposition amount are 0; the N fixation rate is 5 kg N/(ha·year) for nonleguminous crops and 25 kg N/(ha·year) for leguminous crops. The N deposition amount is 1.5 g N/(m²·year). For the nutrient release from the natural area, we simply assume that it is 1/6 of the nutrient release from the agricultural area. Using this nutrient release data along with the data on precipitation, time of concentration (which is 3.3 days estimated using equations in National Engineering Handbook), and the curve number (which is set as an average value of 70), the model calculates the runoff value. The nutrient transport delay in the water body (e.g., from the river to lake) is ignored because this occurs at a faster timescale than the one considered here.

Setting and Data for Algae Growth Model. The algae growth model as described in Figure 5(c) requires input data to capture algal cell information (surface area, volume, maximum dissension, and movement under light conditions), amount of nutrients entering the system, lake volume, average depth, and weather data. In this study, we consider eight algae species that represent the typical species found in lakes with certain properties such as edibility, nitrogen fixation, and fast movement. The algae cell information is obtained from. The lake information is obtained from the Wisconsin DNR. The temperature profile

[^5]: https://www.madsewer.org/
and mixed layer depth throughout the year are generated using the FLAKE model.\textsuperscript{41} The weather conditions, including sunlight intensity and duration of days, are calculated using the SWAT model.\textsuperscript{23}

**Scenario Description**

We study the time-period spanning April to the end of October since HABs are more likely to occur during this period. We begin the analysis by specifying manure storage levels. This helps capture the effects of winter manure application strategy because, if the initial storage level is low, then this indicates that farmers spread manure during the winter. We also specify the initial phosphorus and nitrogen concentrations in the lake to capture its starting nutrient status. In addition to the initial conditions, technology availability needs to be specified to define the scope of manure treatment. We also specify how strict the NMP is in the logistics network by adjusting the penalty coefficients $\lambda^P$ and $\lambda^N$. The logic of this decision-making procedure is summarized in Figure 6. If the algae prediction indicates high risk, we change the setting of the logistics network to adjust the management actions (e.g., increase the use of technologies and increase the environmental cost). We also use the framework to study the impacts of the changes in the logistics network on final HAB results.

We ran eight scenarios in total (listed in Table 1). For the initial condition, we estimate the concentration of phosphorus in the lake using historical data from the Wisconsin DNR. The Wisconsin DNR has annual water quality reports for most lakes in WI, and we select the P concentration in early April in the year 2016 and year 2018 to represent the high and low concentration scenarios, respectively. The low concentration (45 mg P/m$^3$) scenarios correspond to an effective manure winter application strategy (90% manure is stored while 10% is used for winter crops like hay and winter wheat based on the phosphorus need). In contrast, a high nutrient concentration (120 mg P/m$^3$) scenarios correspond to an ineffective manure winter application strategy (70% manure is stored while 30% is applied to land). The storage level here is obtained from a simple calculation that assumes that the initial
phosphorus concentration difference in the lake (75 mg P/m$^3$) is purely caused by the excess manure applied, which is around 20% of the manure generated during winter time.

We also consider scenarios in which separation technologies are and are not used. We assume that the solid fraction after separation can be sold, while the liquid fraction and the raw manure (slurry) are not demanded by external customers due to transportation and storage issues. For the NMPs, in the strict NMP scenarios, the nutrient credit reported in$^{42}$ is used as the penalty coefficient of phosphorus (for nitrogen, we discount the value using the scaling factors from$^{43}$, i.e. 33 USD/kg P and 4.5 USD/kg N) while in the loose NMP scenarios, the coefficient is set to zero. The scenarios are summarized in Table 1. We note that the current condition in the State resembles that of Scenario II and Scenario VI (the initial nutrient concentration is high, most farms do not have NMPs, and only large farms are equipped with technologies).
Table 1: Characteristics of scenarios analyzed.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Winter Storage Percentage</th>
<th>Initial Nutrient Concentration</th>
<th>NMP</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>70%</td>
<td>High</td>
<td>Strict</td>
<td>None</td>
</tr>
<tr>
<td>II</td>
<td>70%</td>
<td>High</td>
<td>Loose</td>
<td>None</td>
</tr>
<tr>
<td>III</td>
<td>90%</td>
<td>Low</td>
<td>Strict</td>
<td>None</td>
</tr>
<tr>
<td>IV</td>
<td>90%</td>
<td>Low</td>
<td>Loose</td>
<td>None</td>
</tr>
<tr>
<td>V</td>
<td>70%</td>
<td>High</td>
<td>Strict</td>
<td>Separation</td>
</tr>
<tr>
<td>VI</td>
<td>70%</td>
<td>High</td>
<td>Loose</td>
<td>Separation</td>
</tr>
<tr>
<td>VII</td>
<td>90%</td>
<td>Low</td>
<td>Strict</td>
<td>Separation</td>
</tr>
<tr>
<td>VIII</td>
<td>90%</td>
<td>Low</td>
<td>Loose</td>
<td>Separation</td>
</tr>
</tbody>
</table>

Results and Discussion

In this section, we analyze the results obtained for the WI case study for different scenarios. We also propose some suggestions from perspectives of logistics network waste management strategies for spatiotemporal HAB control and prevention.

HAB Prediction

The HAB prediction results for all the scenarios obtained from the PROTECH model are presented in Figure 7. Here, the green, yellow, and red dashed lines represent the low, moderate, and high probability HAB onset levels associated with different adverse health effects. The health effects are estimated by the World Health Organization (WHO). The blue solid line is the average chl-a concentration near the lake surface (<0.5 m), where most recreational activities occur.

We observe that, in all scenarios explored, HABs are more likely to occur in summer months (July, August, and early September) due to the higher temperature and favorable sunlight conditions. We also note that the occurrence and severity of HABs depend on the initial concentration of algae in the lake. Calculations confirm that environmental conditions (temperature and sunlight) and phosphorus concentration are the key limiting factors of algal growth. This observation is consistent with the assumption commonly made in many life-cycle analysis methods. Specifically, it is often assumed that phosphorus is the limit-
Figure 7: Average chlorophyll-a concentration near the lake surface (<0.5m) for scenarios considered. The green, yellow, and red dashed lines represent the low, moderate, and high probability levels of acute health effects due to HABs. Blue solid line is the temporal profile achieved by implementing the designed organic waste management logistics network.
Figure 8: Chlorophyll-a concentration in the lake at different depths and times.
ing factor for algal growth in inland surface water while nitrogen is the limiting factor in marine water. Our results show that reducing the chl-a concentration below high-risk levels (Scenario VII) requires a combination of initiatives. Specifically, this can only be achieved by having high levels of winter store, reducing the base nutrient concentration level of the lake, enforcing strict NMP policies, and implementing separation technologies to mobilize waste outside the region. Maintaining chl-a levels at the high-risk levels (Scenarios I, III, VI) requires enforcing strict NMP policies (regardless of the other factors). We thus see that potential NMP policies play a key role in HABs control.

The concentration of chl-a at different depth and time for each scenario is shown in Figure 8. Here, red indicates a high chl-a concentration and blue indicates low chl-a concentration. We can see that algae cells are mainly aggregated at the surface of the lake during the summer time (due to favorable light and temperature conditions). For Scenario II, the surface concentration of chl-a reaches over 300 mg/m$^3$ (corresponding to a cell density of 600,000 cells/ml). Together with the impact of sunlight, slow-moving water, and other natural forces, there is a risk of forming algal scum on the lake surface. For the best scenario (Scenario VII), the surface concentration of chl-a can be reduced by a factor of three (to 100 mg/m$^3$).

From the above analysis, we find that incorporating appropriate logistics network management strategies in storage planning, nutrient application planning, and with the use of nutrient recovery technology, we can reduce the HAB level from a high-risk level to a moderate-risk level within one year. To further reduce the risk of HABs, mid-term efforts (e.g., perennial nutrient management) are necessary. Specifically, when the initial conditions are not favorable for the lake health (representing a poor manure application planning in winter), the predicted HAB level is always higher. In Scenario II, the HAB level can reach the warning level of a high probability of causing acute health impacts to humans. Even with strict NMPs and the use of technologies, the chl-a concentration is still around the warning line (Scenario V). The model does confirm that it is not recommended to apply manure during the winter since the nutrient demand from crops is low and the nutrients accumulated
in the soil will travel to the surface water when the spring runoff occurs. Thus, the winter application activity can impact the HAB situation in the following summer and investing storage systems to manage winter manure is critical to displace the timing of nutrient flows and HABs.

Under the current fertilizer market prices and their nutrient content, farmers prefer to buy fertilizers from retailers instead of storing, transporting, and applying existing animal manure. Therefore, there should be an external driving force to make the system avoid this economically feasible but environmentally unsound solution. One strategy is to achieve this driving force through NMPs. In particular, our results reveal that a strict NMP can reduce the HAB level regardless of technology usage and initial condition (Figure 7). At present, only large CAFOs (concentrated animal feeding operations) and their associated agriculture lands are required to follow NMPs. Small farms are not mandated to follow NMPs and are more likely to use external fertilizers and spread animal waste during winter months.

By using manure separation technologies, we can reduce the HAB level by reducing the amount of excess nutrient in the study region (when there is external demand for products). We also observe that the use of technology can have a larger impact on HAB reduction when combined with strict NMP policies and proper storage planning (Scenario VII).

**Logistics Network Design and Nutrient Pollution**

In addition to the results obtained with the PROTECH model, we can gain insights from the results of the logistics network model. In Figure 9, we present the mobilization (transportation) routes for manure for Scenario V and Scenario VI at different times. The overall inventory levels for manure are presented in Figure 10. For all scenarios, the inventory levels of manure have a similar trend. At the beginning of April, the inventory levels increase because most crops have not been planted and the system needs to store the waste. After the short increase in inventory level, there is a drop because the land nodes need nutrients to support crop growth, and also because the logistics network needs to clear storage space
for the coming inventory in the subsequent winter. This trend is also evident from the transportation maps (Figure 9). For both scenarios, the majority of farms transfer waste to storage systems in early April and then haul the waste agricultural lands in the following months. We also observe that the NMP influences the nutrient output of the logistics network system by adjusting spatial mobilization (transportation) instead of temporal mobilization (inventory levels). For the transportation in Scenario V where the NMP is strict, the transportation routes are longer (more mobilization is needed) because the logistics network is monitoring the locations where nutrients are in demand and the farmers send the animal waste to the exact agricultural land to achieve high efficiency in nutrient reuse. On the other hand, in Scenario VI (under which the NMP is not enforced strictly), the farmers only send the waste to nearest lands to achieve a lower transportation cost. The transportation routes for other scenarios follow similar trends.

Figure 9: Waste transportation logistics in Scenarios V and VI at different times.

In Figure 11 we present the nutrient loading maps for Scenario V, VI, VII at different...
time periods. For Scenario V (Figure 11(i)), due to the relatively low winter storage levels and strict NMP, there is zero excess phosphorus at all time periods. For Scenario VI, since the NMP enforcement is loose and fertilizers are demanded by farmers, the phosphorus is highly imbalanced in the area. For Scenario VII, even though the winter storage level is higher we find that with proper logistic design, a more balanced P distribution is achievable. We also note that most excess phosphorus appears in April when the nutrient demand from crops is relatively small. When the nutrient demand increases, the excess phosphorus decrease. As mentioned earlier, we can draw a similar conclusion that a potential preventive action is to stimulate the involvement of the storage systems before the crops are planted to store the animal waste for later use.

**Trade-off Analysis Between Economic and Environmental Objectives**

Finally, we perform a trade-off analysis between the economic costs (transportation, technology, and fertilizer costs) and the HAB levels by varying the environmental costs (enforcing NMP more strictly) in the logistics network under two settings, presented in Figure 12. The red plane represents the high probability levels of acute health effects due to HABs. Figure 12(a) shows the trade-off with 70% initial storage, high initial nutrient concentration (120 mg P/m$^3$), and the use of separation technology. The environmental costs of excess phosphorus are 0 (Scenario VI), 6.6, 13.2, and 19.8 USD/kg P, respectively. The ratio of the environmental costs of excess phosphorus and nitrogen remain unchanged. From the graph, we find that the cost necessary to keep the curve near the red plane is about 1.25 million USD. To be
Figure 11: Phosphorus loadings in Scenarios II, VI, VII and at different times.
specific, this cost only includes transportation cost and pure operational cost of technology; no additional investment is included. If we further increase the environmental costs, we cannot decrease the HAB level further. In this case, the cost associated with HAB prevention reaches 0.36 million USD given the worst-case cost is 0.89 million USD.

Figure 12(b) shows the trade-off with 90% initial storage, low initial nutrient concentration (45 mg P/m$^3$), and the use of separation technology. The environmental costs of excess phosphorus are zero (Scenario VIII), 6.6, 13.2, 33 (Scenario VII), 46.2, and 66 USD/kg P, respectively. The cost to keep the curve under the red plane is still around 1.40 million USD. We note that our estimate of prevention cost is conservative because it does not factor in storage cost, cost related to policy implementation, and cost of technology development and investment. Additionally, if we compare the two cases we studied, we find that when the starting condition is relatively better (high winter storage and low nutrient concentration), we have the option to spend more money in the logistics and inventory planning to avoid nutrient runoff and reduce the HAB levels to a relatively large extent compared to present conditions. On the other hand, if the starting condition is not favorable (initial storage is low and the nutrient has already entered the lake), a small reduction in the HAB levels can be achieved. Since the current situation in the study area is closer to the worse case, mid and long-term prevention efforts and remediation actions (e.g., direct lake cleaning, HAB scum removal) will be needed to control the nutrient runoff from agricultural lands and to accelerate the recovery of the lake.
(a) Trade-off analysis with 70% initial storage, high initial nutrient concentration, and use of separation technologies

(b) Trade-off analysis with 90% initial storage, low initial nutrient concentration, and use of separation technologies

Figure 12: Trade-off analysis between economic costs and nutrient pollution levels.
Concluding Remarks and Future Work

In this work, we presented a computational framework to manage organic waste from agriculture activities for reducing and preventing nutrient pollution and HABs. We employed an existing nutrient fate and transport model NEWS2, and an algae growth model PROTECH, to study the impact of the decisions made in the logistics network management on the environment. This modeling framework can be used to predict if a HAB will occur in the worst case and if offhand preventive actions are enough to prohibit the occurrence by controlling the related environmental conditions. We also provided a case study for the Upper Yahara Watershed in the state of Wisconsin to show the practicability of the modeling framework. We have found that the logistics network management for waste and nutrients can reduce the incidence rates of HABs effectively but reducing to a non-harmful level may require long-term efforts such as installing advanced manure treatment technologies and storage systems. We study the impact of different nutrient pollution control strategies including manure application planning in winter, the use of nutrient management plans and technologies. We found that all three strategies can reduce nutrient release by a certain amount, and by extension reduce the level of HABs. Among them, using strict nutrient management plans can achieve the best immediate effects, and manure application planning in winter has a significant influence on the occurrence of HABs in the following summer. The three strategies have synergistic effects in the sense that, when applied together, they can reduce the HAB levels by the greatest extent. In addition, this contribution aims to offer more realistic nutrient pollution prevention and control costs and employ this framework for the design and evaluation of feasible and efficient nutrient management incentives and policies.

In the future, we plan to extend our framework to incorporate a perennial setting and to use more site-specific soil and crop data (to include the legacy phosphorus in the soil). This will help us understand the long-term impact of nutrient management strategies using a more accurate nutrient transport modeling tool to simulate soil-hydrology transport and winter runoff. We also seek to reformulate the logistics network design problem into a
general temporalspatial market clearing problem and derive the internal prices of products, transportation, and technologies to understand the economic impact of having HABs.

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Nomenclature for Logistics Network Model

Variables

- $I_{i,p,\tau}$ - inventory level of material $p$ at node $i$ and at the end of time period $\tau$
- $f_{i,j,p,\tau}$ - transportation flow of material $p$ from node $i$ to node $j$ at time period $\tau$
- $g_{i,t,p,\tau}$ - the generation amount (consumption if negative) of material $p$ through technology $t$ at node $i$ and at time period $\tau$
- $d_{i,p,\tau}$ - demand value of material $p$ at node $i$ and at time period $\tau$
- $x_{i,p}$ - binary variable to indicate the installation of storage system for material $p$ at node $i$
- $y_{i,t}$ - binary variable to indicate the installation of technology $t$ at node $i$
- $NP_{i,\tau}$ - net excess phosphorus at node $i$ and at time period $\tau$
- $NN_{i,\tau}$ - net excess nitrogen at node $i$ and at time period $\tau$
- $ferP_{i,\tau}$ - phosphorus from fertilizers at node $i$ and at time period $\tau$
- $ferN_{i,\tau}$ - nitrogen from fertilizers at node $i$ and at time period $\tau$
- $C_{inv}$ - total investment cost
- $C_{trans,\tau}$ - total transportation cost in time period $\tau$
- $C_{op,\tau}$ - total operational cost in time period $\tau$
- $C_{fer,\tau}$ - total fertilizer cost in time period $\tau$
- $C_{sup,\tau}$ - total supply cost in time period $\tau$
- $R_{\tau}$ - total revenue in time period $\tau$
Parameters

\( s_{i,p,\tau} \) - supply value of material \( p \) at node \( i \) and at time period \( \tau \)
\( \alpha_{t,p} \) - yield factor of material \( p \) in technology \( t \)
\( p_{\text{pref}(t)} \) - the reference material of technology \( t \)
\( \bar{d}_{i,p,\tau} \) - demand capacity of material \( p \) at node \( i \) and at time period \( \tau \)
\( \bar{I}_{i,p} \) - storage capacity of material \( p \) at node \( i \)
\( C_t \) - reference capacity of technology \( t \)
\( \bar{f}_{i,j,p,\tau} \) - capacity of the transportation flow of material \( p \) from node \( i \) to node \( j \) at time period \( \tau \)
\( e_{P,p} \) - phosphorus emission coefficient of material \( p \)
\( e_{N,p} \) - nitrogen emission coefficient of material \( p \)
\( Pd_{i,\tau} \) - phosphorus demand of crops at node \( i \) and at time period \( \tau \)
\( Nd_{i,\tau} \) - nitrogen demand of crops at node \( i \) and at time period \( \tau \)
\( C_{\text{inv},t} \) - investment cost of technology \( t \)
\( C_{\text{inv},p} \) - investment cost of the storage system for material \( p \)
\( \beta \) - depreciation factor for the investment cost of technologies
\( \gamma \) - depreciation factor for the investment cost of storage systems
\( D_{i,j} \) - distance between node \( i \) and node \( j \)
\( C_{\text{trans},p} \) - transportation cost of material \( p \) per unit distance and per unit of flow
\( C_{\text{op},t} \) - operational cost of technology \( t \) when processing one unit of reference material
\( \rho^P \) - market price for one unit of phosphorus in fertilizer
\( \rho^N \) - market price for one unit of nitrogen in fertilizer
\( \rho^s_{i,p,\tau} \) - supply price of material \( p \) at node \( i \) and at time period \( \tau \)
\( \rho^d_{i,p,\tau} \) - demand price of material \( p \) at node \( i \) and at time period \( \tau \)
\( \lambda^P \) - environmental cost per unit excess phosphorus
\( \lambda^N \) - environmental cost per unit excess nitrogen
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