Environmental Science & Technology

pubs.acs.org/est Article

Integrated Agricultural Practices and Engineering Technologies Enhance Synergies of Food-Energy-Water Systems in Corn Belt Watersheds

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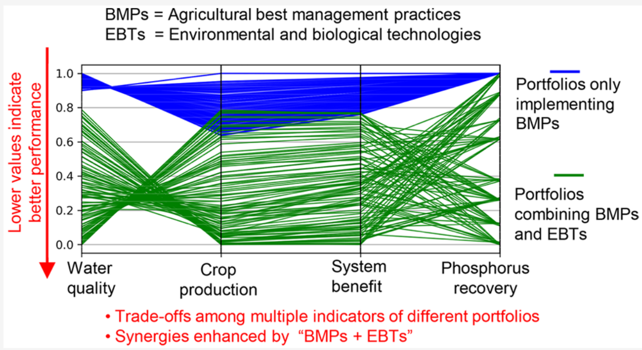
Cite This: *Environ. Sci. Technol.* 2023, 57, 9194−9203 Read Online

ABSTRACT: Interconnected food, energy, water systems (FEWS) require systems level understanding to design efficient and effective management strategies and policies that address potentially competing challenges of production and environmental quality. Adoption of agricultural best management practices (BMPs) can reduce nonpoint source phosphorus (P) loads, but there are also opportunities to recover P from point sources, which could also reduce demand for mineral P fertilizer derived from declining geologic reserves. Here, we apply the Integrated Technology-Environment-Economics Model to investigate the consequences of watershed-scale portfolios of agricultural BMPs and environmental and biological technologies (EBTs) for co-benefits of FEWS in Corn Belt watersheds. Via a pilot study with a representative agro-industrial watershed with high P and nitrogen discharge, we show achieving the nutrient reduction goals in the watershed; BMP-only portfolios require extensive and costly land-use change (19% of agricultural land) to perennial energy grasses, while portfolios combining BMPs and EBTs can improve water quality while recovering P from corn biorefineries and wastewater streams with only 4% agricultural land-use change. The potential amount of P recovered from EBTs is estimated as 2 times as much as the agronomic P requirement in the watershed, showing the promise of the P circular economy. These findings inform solution development based on the combination of agricultural BMPs and EBTs for the cobenefits of FEWS in Corn Belt watersheds.

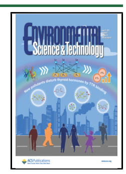


KEYWORDS: *FEW nexus, Watershed approach, Trade-offs and synergies, Phosphorus recovery, Environmental benefit*

INTRODUCTION

The food, energy, and water systems (FEWS) in Corn Belt watersheds are multifunctional systems that jointly produce crops (mainly corn and soybean), food products, animal feed, ethanol, water (for both the environment and domestic use), and other ecosystem services.[1,2] These functions generate socioeconomic benefits along with high energy consumption, nutrient discharge,[3,4] and interconnected risks to food, energy, and water sectors.[5,6] Specifically, crop production in the region faces challenges from weather variability, pests, input price fluctuations, nutrient loss, soil erosion, and calls to reduce fertilizer usage.[7,8] Intensive fertilizer use in crop production and expansion of corn-based ethanol production have led to high nutrient loading to water bodies and require increased energy use and costs for drinking water and wastewater treatment[9] while accelerating aquatic vegetative growth and ecosystem disruptions.[10] Phosphorus (P), a key component of fertilizers and a major contributor to the harmful algal blooms[11] in the Great Lakes and the "Dead Zone" in the Gulf of Mexico, plays a complicated role within the FEWS.[12,13] A particular concern for the region is the so-called P paradox—too much P from agricultural production and food processing polluting water bodies despite a decline of phosphate rock reserves for P fertilizer.[14,15] For example, the Sanitary District of Decatur, which treats wastewater from ADM and other major food companies, is one of the largest point sources of P in Illinois, and it contributes to the increased P load to the Illinois River.[16] Other substances (e.g., N and sediment) that affect water quality should be included in analyses and discussions evaluating strategies for water quality improvement. However, the opportunities for recovering P from point

Received: March 20, 2023
Revised: May 11, 2023
Accepted: May 15, 2023
Published: May 31, 2023



sources, which could reduce both riverine P loads and P demand from declining geologic reserves, have not been well-studied and deserve in-depth analysis to address potentially competing challenges of food production and environmental quality. In addition, in the case study watershed (where Decatur is located), large quantities of P discharge from point sources is a major issue of concern.

Recently, efforts have been dedicated to the development of FEWS models at different scales (e.g., communities,[5] cities,[17] watersheds,[3] regions,[5] countries[18]) using different modeling approaches (e.g., nexus accounting,[17] system dynamics,[19] system of systems[3]). A holistic systems framework is also needed to address these issues of FEWS in the Corn Belt with a unique problem—high P and N discharge affecting drinking water locally[20,21] and the hypoxic zone in the Gulf nationally.[22] However, at present, disciplinary-specific efforts have resulted in siloed solutions that ignore or do not fully consider the impact of the FEWS nexus interactions.[5] For example, for water quality control, individual projects that focus on point or nonpoint sources have been undertaken separately.[23−28] At the watershed scale, agricultural best management practices (BMPs) are usually implemented to reduce the nonpoint nutrient contribution to water bodies;[23−26] however, those efforts often leave out the impact of point-source discharges from wastewater treatment plants and industry. Meanwhile, environmental engineers and biological engineers have investigated technologies on nutrient removal for point-source reduction and nutrient recovery, such as struvite.[27−31] Unfortunately, nutrient recovery is often studied in disciplinary-specific models (e.g., biorefinery, wastewater), without considering the impact on other processes at the watershed scale.[28,30,31] For example, recovering P from a corn biorefinery can result in lower P in animal diets, which reduces P concentration in animal manure and reduces the probability of nonpoint source pollution from livestock manure in watersheds where animals are fed with reduced P content rations. Moreover, novel environmental and biological technologies (EBTs) often come with relatively high engineering cost.[30,31] Thus, understanding the interactions and complementarities among multiple interconnected physical processes (e.g., nutrient loading from landscape runoff and point-source discharges, reservoir trapping, and in-stream transport and deposition) is critical for optimizing point and nonpoint source nutrient management and efficiently achieving nutrient reduction targets.[1,4] Coordinated implementation of those practices requires interdisciplinary collaboration and knowledge transfer beyond the current status quo in silos.

As traditional watershed management studies lack the integration of agricultural and engineering systems, the importance of coordinating nonpoint source and point-source nutrient recovery and management has not been addressed with depth. To help decision-makers in Corn Belt watersheds address interrelated challenges and identify opportunities, we developed the Integrated Technology-Environment-Economics Model (ITEEM) tool[3] that captures essential technology-environment-economics relations and can be used to explore insights on the FEWS nexus, which are not available from single-discipline modeling efforts. To this end, we couple the ITEEM with an optimization algorithm to systematically investigate portfolios that can most efficiently achieve the cobenefits (i.e., water quality, food production, economic benefits, P recovery) of FEWS in Corn Belt watersheds. We address the following key question: whether portfolios consisting of BMPs and EBTs can be optimized to provide environmentally acceptable and economically feasible solutions for the sustainable management of nutrient pollution from FEWS in Corn Belt watersheds. The core hypothesis of this study is agricultural BMPs must be accompanied by cutting-edge EBTs in watershed management portfolios to effectively manage the FEWS in Corn Belt watersheds.

■ METHODS

In this study, we apply the ITEEM to investigate watershed-scale portfolios of agricultural BMPs and EBTs via a case study in a typical Corn Belt watershed. The physical, biophysical, and chemical processes involved in the integrated model were validated by historical data (see refs 27, 29, 30, 32 for more details); the economic parameters and relations are validated by Parthum and Ando.[32] The ITEEM is coupled with a multiple-objective optimization program to illustrate the trade-offs and synergies among the food, energy, water, and environment systems and to explore solutions based on spatially explicit combinations of agricultural BMPs and EBTs.

An Integrated Modeling Tool for Identifying Holistic Solutions at a Watershed Scale. This study applies the Integrated Technology-Environment-Economics Model (ITEEM) that incorporates the interdependencies among food, energy, and water sectors in a typical Corn Belt watershed. Specifically, five model components are included in ITEEM: (1) the Soil and Water Assessment Tool (SWAT) to simulate the impact of spatially distributed BMPs on watershed water quality, water quantity, and crop production; (2) wastewater treatment (WWT) models to evaluate treatment alternatives that impact point-source nutrient (both NO_3−N and P) effluents at a monthly scale and P recovery potential as struvite;[28] (3) corn biorefinery (CB) models developed using SuperPro Designer (Intelligen, Inc.) to investigate the potential for P recovery and assess energy consumption;[30,31] (4) a drinking water treatment model (DWT) that responds to nitrate and sediment inputs from SWAT to simulate the impacts of upstream agriculture on energy costs for nitrate and sediment removal; and (5) an empirical economic model[3] that evaluates system-level benefits and the nonmarket value of water quality improvement based on a survey of the public. The five individual component models are integrated using surrogate models developed by various data-based modeling techniques (e.g., a modified response matrix method for SWAT,[33] a machine learning approach for surrogating plant-wide WWT models[28]). Detailed information about the component models, their surrogates, the interactions between the components, and the architecture of the integrated model are provided in a previous article.[3]

For the agricultural BMPs, we designed different BMP combinations consisting of P fertilizer application reduction (15 or 30% reduction), cover crop (a winter cover after corn), tillage practice (reduced tillage in fall), and edge-of-field/riparian practices (filter strips, grassed waterways). Land-use change converting cropland or marginal land to perennial energy grasses has attracted attention under the cellulosic biofuel mandate in the Renewable Fuel Standard Program.[7,34] In this study, we consider land-use change consistent with an expansion of perennial grass crops as one additional BMP. Details regarding the simulation of those BMPs are provided in Section 1 and Table S1 of the Supporting Information (SI). EBTs include five wastewater treatment technology alternatives for removing and potentially recovering P: (1)

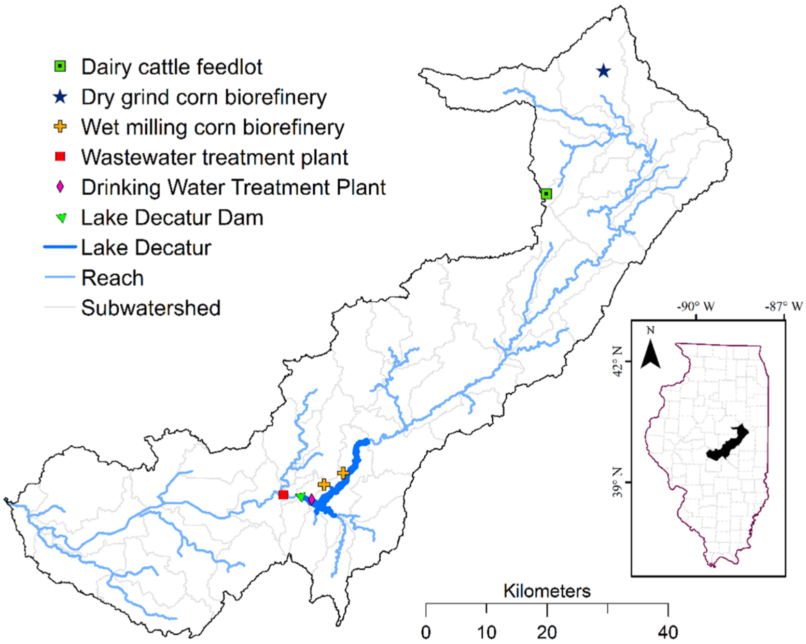


Figure 1. Map of Upper Sangamon River Watershed (USRW) with plant locations for engineering systems and a dairy cattle feedlot.

activated sludge (AS) as the status quo, (2) AS with chemical precipitation (ASCP), (3) modified Bardenpho enhanced biological phosphorus removal (EBPR), (4) EBPR with acetate addition (EBPR-A), and (5) EBPR with struvite recovery (EBPR-S). The EBTs also include two biological engineering technologies: wet-milling and dry-grind corn biorefinery models, each of these models including two options: no P recovery and P recovery. Lists of BMPs and EBTs used in ITEEM optimization are provided in SI Table S2.

The interaction of SWAT with WWT and CBs are simulated by (1) using manure as land-applied fertilizer with reduced P for a dedicated subwatershed that receives manure from a nearby animal feedlot; (2) using sludge as land-applied fertilizer based on different WWT alternative technologies deployed in the subwatershed where the WWT is located. More details on simulations of BMPs, manure, and biosolid applications are provided in SI Section 1. Overall, the ITEEM allows the identification of watershed management portfolios to manage FEWS.

Multiple-Objective Optimization Framework. A multiple-objective optimization framework is usually employed to assess trade-offs and synergies. According to Pareto optimality, trade-offs exist among the set of noninferior solutions that form a frontier, such that a gain in one objective leads to a loss of some other(s). In this work, we hypothesize that a collection of noninferior solutions consisting of only BMPs can be improved by combined solutions consisting of BMPs (including land-use change) and engineering technology innovations and thus provide positive synergy (i.e., win-win for some objectives) to the FEWS in Corn Belt watersheds.

Objective Function. Four objectives represent the multidimensional functions of the FEWS: (1) system benefit, (2) water quality, (3) crop production, and (4) P recovery. The first objective, system benefit, quantifies the net economic benefits, which is the difference between the revenue from product sales, nonmarket valuation of associated water quality improvements, and costs of BMPs and the engineering systems (WWT, DWT, CB). Because different systems have different lifespans, we use equivalent annual cost (EAC) to combine one-time and ongoing costs and benefits into an annual cost stream to quantify the annualized monetary net benefits for the entire system. The second objective, water quality, is quantified using nitrate and TP mass discharge. The third objective, crop production, accounts for corn and soybean mass production. Furthermore, we include the amount of P recovery (including the mass amount of P recovered from WWT and CB) as one objective, given the role of P recycling to address P paradox.[29] Although energy demand can be an objective in managing FEWS, we do not include it as an objective because the change in energy demand associated with the three engineering systems (WWT, CB, and DWT) in different watershed solution portfolios is negligible (less than 1% change). All objectives are assigned equal weight and are normalized between 0 and 1 to facilitate efficient solution convergence. Detailed objective formulations are provided in Appendix SI, Section 2.

Decision Variables. The decision variables include agricultural BMPs and EBTs. We initially considered a total of 55 candidate agricultural management practice combinations that include adding a winter cover crop, P fertilizer reduction, or expanding land area in filter strips or grassed waterways, from which the five most cost-effective were selected based on performance of TP and NO_3−N reduction. Perennial energy grasses were also selected as an option because of their large nutrient reduction potential. Details on selecting the five most cost-effective BMP combinations are provided in SI, Section 3. We further cluster the spatially distributed BMP combinations from subwatershed scale to subwatershed clusters using k-means clustering to reduce the number of decision variables at spatial scale (see details in SI, Section 4). An integer decision variable (0−4) is used for the selection of the dominant wastewater treatment plant from five treatment alternatives that remove and recover P by chemical or biological processes. Three binary variables are defined with three corn biorefineries

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Environ. Sci. Technol. 2023, 57, 9194−9203

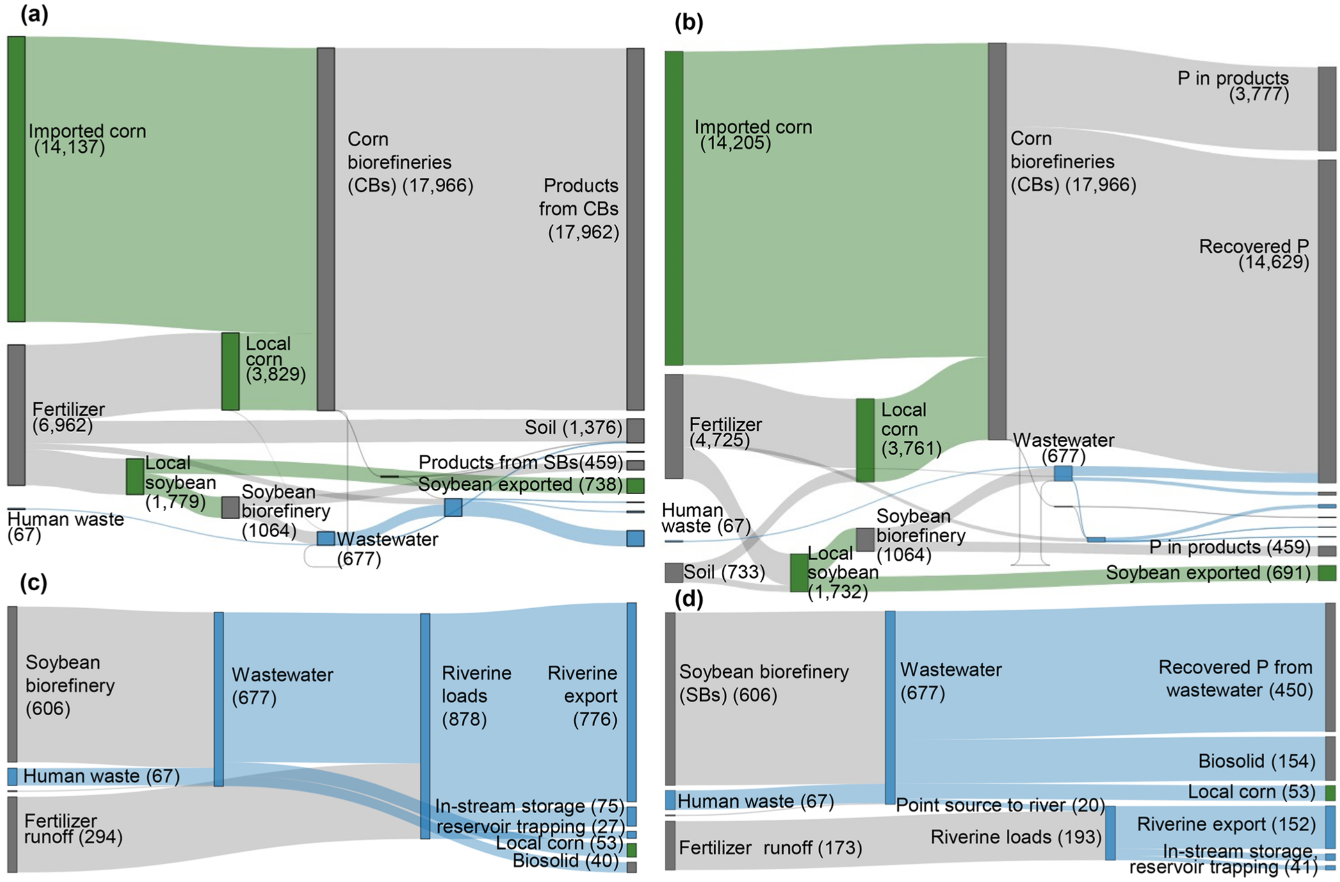

Figure 2. Phosphorus (P) flow at the watershed scale under two scenarios during 2012−2018: baseline (a) and alternative scenario (b) (adoption of BMPs + engineering technology upgrade). All values presented are in metric ton per year (MT yr^{-1}). Detailed P flows related to point and nonpoint source pollution in (a) and (b) are provided in (c) and (d), respectively. All forms of P inputs and outputs are expressed as mass of elemental P regardless of specific forms. Specifically, the elemental P content of P recovery products from a corn biorefinery is 26.4% based on the experimental findings. The elemental P content of diammonium phosphate as fertilizer is 20%. The organic and inorganic P from nonpoint sources were simulated by SWAT and accounted as TP. The point-source P was simulated as TP in the form of elemental P by GPS-X software. Imported corn was calculated based on the plant capacity of biorefineries, while the production of local corn and soybean was obtained from the SWAT simulation, which has been validated based on the historical corn and soybean production;[42] P content in corn and soybean on a dry basis is assumed to be 0.33% and 0.63%, respectively, based on a survey of more than 2000 corn and soybean grain samples in Illinois.[43] Other P flows were simulated in the integrated model based on their elementary P in each process.[3]

(two wet-mill facilities and one dry-grind facility) for selection between status quo (no P recovery) and P recovery.

Constraints. The maximum allowable area for application of BMP combination is constrained by the total agricultural land available in each subwatershed. We impose a minimum 15% reduction in the annual average NO_3−N and TP loads at the outlet because water quality improvement is particularly important in the study area due to its contribution to nutrient pollution in the Gulf of Mexico. This constraint is the intermediate reduction target for NO_3−N is 15%, while the intermediate reduction target for P is 25% by 2025 in Illinois.[35] A 15% reduction constraint was applied to both N and P at the outlet because a 25% P reduction is not feasible under the "BMP-only" solutions. In practice, this means that solutions exist when only considering agricultural BMP adoption without EBTs during the optimization process.

Algorithm. We applied a fast and elitist multiobjective genetic algorithm with reference directions (NSGA-3)[36] using the Pymoo package[37] in Python. Evolutionary algorithm iterations were stopped upon the maximum evaluations (25 000 runs) or/and when objective values are improved less than 0.5% for the last 20 generations. To evaluate the roles of BMPs and EBTs on FEWS performance, we run the optimization model under two settings: (1) "BMP-only", considering the spatially distributed BMPs (60 decision variables in total) only, with existing engineering technologies. (2) "BMPs + EBTs": considering spatially distributed BMPs plus EBTs (one variable for WWT and three variables for three CBs).

A Typical Agro-industrial Watershed. The Upper Sangamon River Watershed (USRW) located in Central Illinois, with a size of 3732 km^2, is used as the case study area (Figure 1). The USRW, a watershed with about 90% of land cover being cultivated agricultural land, faces issues related to both agricultural runoff and municipal and industrial nutrient discharges. The combination of subsurface (tile) drainage with continuous annual row cropping (generally corn and soybeans), high organic matter soils, and high fertilization rates commonly lead to nutrient pollution and nitrite concentrations that periodically exceed the maximum contaminant level (10 NO_3−N mg L^{-1}) based on US National Primary Drinking Water Regulations.[38] As a result, energy consumption and cost of public drinking water supplies for reducing nitrate concentrations in the USRW are increased,

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Environ. Sci. Technol. 2023, 57, 9194−9203

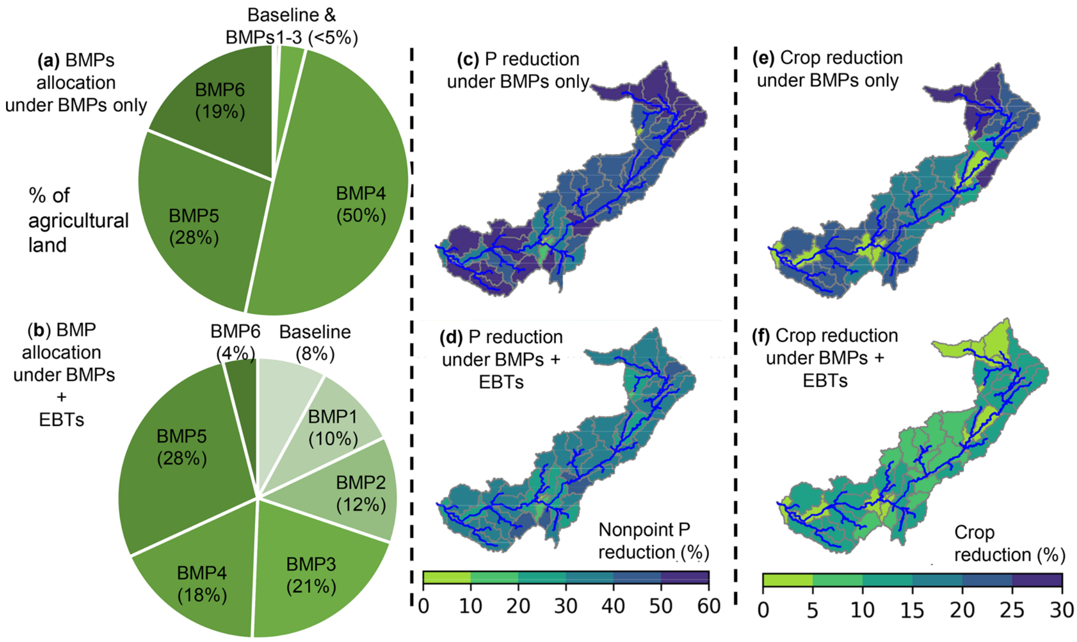

Figure 3. Impact on nonpoint P and crop production under "BMP-only" and "BMPs + EBTs": BMPallocation (a,b), spatial nonpoint source phosphorus (P) reduction (c,d), and crop reduction (e,f). BMP combinations 1−6 are provided in Table S2. BMP combinations 1−3 are less comprehensive compared to BMP combinations 4−5. BMP combination 6 is a land-use change to perennial grasses. Values in pie charts (a,b) represent the averaged % of agricultural land that adopts a specific BMP combination from optimal solutions.

like many other flat, tile-drained, and intensively cultivated watersheds in the Corn Belt.[20,39,40] Lake Decatur in the watershed serves as the source for industrial and municipal water supply in City of Decatur. Sediment deposited in Lake Decatur affects both active storage and water quality and requires costly sediment dredging. The City recently completed a $92 million lake dredging program to increase storage in the lake, as over one-third of the storage capacity was lost due to sedimentation, which is equivalent to around $23 per metric ton of sediment dredged based on an internal report from City of Decatur, IL. Along with sediment, a portion of riverine P from the watershed upstream of the Lake is also deposited in the Lake. Consequently, BMPs for reducing sediment and P loss implemented upstream of the Lake provide benefit to the Lake and water treatment cost, but the impact of these BMPs on P and sediment loads at the watershed outlet will limited by deposition in the Lake. Furthermore, the uncertainties in BMP performance and P deposition in the Lake complicate schemes for nutrient reduction trading between point and nonpoint sources.

Additionally, the USRW has one of the largest point-source total P dischargers in Illinois. The Sanitary District of Decatur (a wastewater treatment plant) treats the municipal and industrial wastewaters with P concentration averaging about 15 mg P L^{-1} from biorefineries that process corn and soybean.[8] The Sanitary District of Decatur discharges into Sangamon River downstream from Lake Decatur. Point-source TP contributes about 70% of the TP loads at the watershed outlet. Technology upgrades are needed to comply with a monthly average effluent concentration P limit of 1 mg P L^{-1}, effective in 2030. Three corn biorefineries (CBs), including two wet-milling plants and one dry-grind plant located in the USRW, produce corn gluten feed and distillers dried grains with solubles as coproducts, respectively. Both coproducts can be sold as an ingredient for animal diets. P recovery opportunities exist in aqueous streams of both wet-milling and dry-grind biorefineries and therefore reduce the P content in byproducts.[30,31] The P loss from manure will further be reduced if animal is fed with reduced P content as diets.

RESULTS AND DISCUSSION

Phosphorus Flow in Agricultural and Engineering Systems at Watershed Scale. As mentioned earlier, the P paradox is one of the key issues interconnected with FEWS in Corn Belt watersheds. To illustrate the potential of P recovery from the engineering systems and the impact on riverine P loads, we compare the business as usual (BAU) to an alternative scenario of nutrient loss reduction control measures. The BAU scenario includes the status quo of agricultural management practices and existing EBTs, while the alternative scenario simulates the BMP combination (cover crop, 30% fertilizer reduction, and 50% of filter strip implementation), EBPR-S for wastewater treatment, and P recovery in three CBs (Figure 2). The majority (14 137 MT yr^{-1}) of P is embedded with imported corn as the raw materials for corn biorefinery, while the P fertilizer requirement is 6962 MT yr^{-1} (Figure 2a). P in manure (68 MT yr^{-1}) and human waste (67 MT yr^{-1}) is relatively much smaller compared to P in fertilizer and imported corn (Figure 2a).

The BAU nonpoint source P and point-source P contribute 34 and 66%, respectively, to the riverine loading (Figure 2c). Note that contribution of point-source P to total riverine loading is 66% while its contribution to the outlet is about 70% (mentioned the previous section) because of the trapping impact on nonpoint source P from an upstream reservoir. By upgrading WWT technologies, point-source P is reduced from 582 to 20 MT yr^{-1} in the alternative scenario (Figure 2d); the nonpoint source P is reduced by 123 MT yr^{-1} as a result of a 30% reduction in P fertilizer application and the adoption of filter strips and cover crops. The alternative scenario recovers P from CBs and WWT facilities. The CB plants recover 14 143 MT P yr^{-1}, which can be exported as P product, and is about

https://doi.org/10.1021/acs.est.3c02055
Environ. Sci. Technol. 2023, 57, 9194−9203

twice the BAU demand of P fertilizer in the USRW. Applying the P recovery technology in CB plants not only reduces the demand for P mining, it also reduces the probability of P in runoff from manure excreted by cattle feed (e.g., corn gluten feed, distillers dried grains with solubles). It is noted that CBs have no impact on point-source P discharge, because there is little wastewater P from the CBs. The alternative scenario demonstrates that, if recovered efficiently, 14 629 MT yr^{-1} of the P contained in corn can supply the entire 6962 MT yr^{-1} P fertilizer requirement for the USRW. (Figure 2a,b). Compared to P recovery in CB plants, the potential of P recovery from WWT plants is much lower (450 MT yr^{-1}). But this recovery can reduce the P discharged to the Sangamon River by more than half. By coupling WWT technologies with the agricultural BMPs, riverine TP loads in the Sangamon River can be reduced from 776 to 152 Mt yr^{-1}. It is noted that P in corn imports dominates the P flow in the testbed watershed, given the fact there are three major corn biorefineries. We demonstrate that the potential of P recovery and how it would change the P flow at the watershed scale via the simulations of integrated model, which offers insights into coordinated agricultural and industrial management of P. A major emphasis in our research has been on exploring opportunities and consequences of recovering P from wastewater and grain processing and thereby reducing riverine P loads and the potential for harmful algal blooms (HABs) and other impairments downstream. However, understanding the multiple factors, including P, that cause the occurrence of HABs requires additional research[41] that is beyond the scope of our study.

Critical Role of Land-Use Change for BMP-Only Portfolios. It is noted that a 45% reduction of riverine nutrient pollution has been proposed for many Corn Belt watersheds to address local water quality problems and hypoxia in the Gulf of Mexico.[5] However, the results with USRW show that implementing agricultural BMPs alone will not be sufficient for the testbed watershed to meet the 45% reduction in TP loads. Overall, Figure 3 demonstrates that a large investment in engineering technologies is needed to meet nutrient pollution reduction goals while avoiding a large land-use change to perennial grass, thus mitigating trade-offs between water quality and crop production.

To evaluate the roles of BMPs and EBTs regarding the FEWS performance measured by the multidimensional metrics, we compare the portfolios obtained from optimization results under two settings: (1) BMP-only and (2) BMPs + EBTs. The results show that portfolios with siloed "BMP-only" require more comprehensive BMP adoption to reach nutrient discharge targets (Figure 3a) than BMPs + EBTs (Figure 3b). As shown in Table 1, BMP combinations 1−3 are considered as less comprehensive practices because they do not include a comprehensive list of BMP choices that can reduce nutrient loss from the various sources; BMP combinations 4 and 5 have a higher potential on removing nutrients because they apply all three individual BMP choices, including cover crop, fertilizer rate reduction, grassed waterways, or filter strips. BMP6 represents a substantive land-use change (LUC) to perennial energy grasses. However, BMPs 4−6 are less cost-effective in terms of dollar per kg nutrient removed than BMP combinations 1−3 (SI, Table S3). The land-use change of BMP6 is particularly important to meet the nutrient reduction target without EBTs. As a result, drastic LUC (19%) is needed for the BMP-only portfolios; while only a moderate LUC (4%) is needed for "BMPs + EBTs" portfolios (Figure 3a,b). In reality, the 19% LUC may not be feasible in a short-term planning period without a well-established infrastructure and market for biomass and lignocellulosic biofuel.[7] Thus, the "BMPs + EBTs" plus a moderate LUC is more promising for managing FEWS in the study watershed USRW and other watersheds facing similar issues in the Corn Belt.

Table 1. Best Management Practice (BMP) Combinations Evaluated in the Study[a]

BMP combination	Cover crop practice	Fertilizer reduction (%)	Edge-of-field/riparian practices
BMP1	none	30%	FS
BMP2	none	30%	GW
BMP3	CC	30%	na
BMP4	CC	30%	FS
BMP5	CC	30%	GW
BMP6	Land-use change to switchgrass		

[a]Note: Each BMP combination includes three individual practices: (1) cover crop practice: none = no cover crop applied; CC = a winter cover crop after corn; (2) fertilizer practice: 30% = fertilizer reduction from baseline (207 kg diammonium phosphate per hectare); (3) edge-of-field/riparian practices: filter strip (FS); grassed waterways (GW).

Figure 3c,d and e,f show the spatially distributed reduction of nonpoint P and crop production (i.e., corn and soybean), respectively. The nonpoint P reduction is 44.5%, and crop reduction is 17.8% for "BMP-only", compared to 31.2% P reduction and 6.5% crop reduction for "BMPs + EBTs" portfolios. Thus, with the contribution of engineering technologies, the typical trade-offs between water quality and crop production can be mitigated for the test watershed; that is, nonpoint P reduction can be substituted by point P reduction, and thus, crop reduction is mitigated due to less land-use change to perennial grasses as well as a smaller reduction of fertilizer.

Synergies and Trade-Offs for Watershed Portfolios Combining BMPs and EBTs. When comparing portfolios under two settings ("BMP-only" vs "BMPs + EBTs"), one major finding from Figure 4a is that watershed portfolios combining BMPs and engineering technologies synergistically enhance water quality, crop production, system benefits, and P recovery. This is because that innovation in engineering technologies can make considerable contributions to achieve nutrient pollution reduction targets without significant land-use change to perennial grasses as discussed before (Figure 3). When evaluating the noninferior solutions within each of the two settings, the line gaps among different "BMPs + EBTs" solutions are large with the objectives of water quality, system benefit, and P recovery, compared to the line gaps among the solutions of "BMP-only". For example, the water quality objective value ranges from 0.90 to 1.0 (line gap, $\Delta = 0.10$) for "BMP-only" and 0 to 0.79 (line gap, $\Delta = 0.79$) for "BMPs + EBTs", which indicates larger opportunities for water quality improvement with "BMPs + EBTs" than BMP-only. The same finding applies to the objectives of crop production, system benefit, and P recovery. For crop production, although the line gaps with each setting are similar (around 0.5), all solutions under "BMPs + EBTs" perform better than "BMP-only" in terms of crop production.

When it comes to the different treatment technologies applied within the setting of "BMPs + EBTs", 63 out of 100 solutions select EBPR with struvite recovery (EBPR-S) as the

https://doi.org/10.1021/acs.est.3c02055
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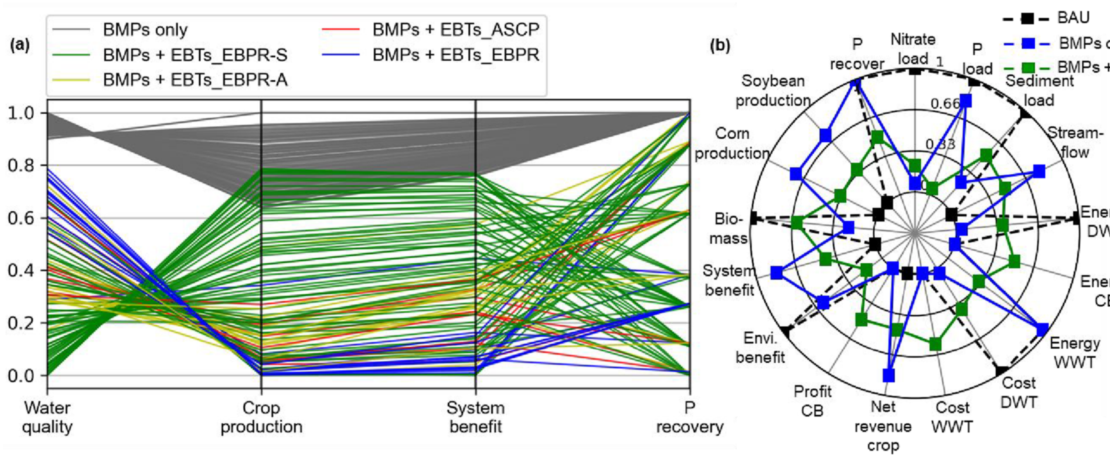

Figure 4. Parallel coordinates of noninferior solutions under "BMP-only" as shown by gray lines, while solutions under "BMPs + EBTs" are shown in four different colors, indicating different wastewater treatment technologies. For example, "BMPs + EBTs_ASCP" represents the portfolio that chooses ACSP as the wastewater treatment technology. Results are normalized between 0 and 1 with lower values indicating better performance; the normalized values of these multi-dimensional outputs as well as their descriptions are provided in SI Section S5. Each line represents a noninferior solution derived from the multiobjective optimization algorithm (Figure 4a). Averaged multi-dimensional outputs of FEWS are presented under two groups of portfolios and baseline: (1) BMP-only; (2) BMPs + EBTs (Figure 4b). Note: BMPs = best management practices; EBTs = environmental and biological technologies; ASCP = activated sludge with chemical precipitation, EBPR = modified Bardenpho enhanced biological phosphorus removal, EBPR-A = EBPR with acetate addition, EBPR-S = EBPR with struvite recovery; CB = corn biorefinery; DWT = drinking water treatment; WWT = wastewater treatment.

point-source treatment technology due to its cobenefit to water quality improvement and P recovery. The remaining 37 solutions are distributed to the treatment technologies of AS-CP (9 solutions, chemical P removal method), EBPR (14 solutions, basic biological P removal method), EBPR-A (14 solutions, biological P removal method with acetate addition). It is also observed that solutions with BMPs + EBTs and EPBR-S can achieve the greatest water quality improvement while having lower crop production as a trade-off. This is because in those solutions, the fraction of land-use change to energy biomass is high in order to achieve the highest water quality improvement, which reduces land for food and feed crops, which will likely shift production to less productive land in other watersheds. To provide more specific portfolios for watershed management, we investigated the noninferior portfolios of "BMPs + EBTs". Specifically, the portfolio with EBPR-S (a WWT technology), P recovery in the dry-grind corn biorefineries, and BMP scenario (i.e., BMP1 − 32.3%, BMP2 − 23.0%, BMP3 − 7.7%, BMP4 − 6.8%, BMP5 − 2.7%, BMP6 (LUC) − 0.4% on the agricultural land) would have the best performance in terms of the system benefit, crop production, and decent P recovery potential (1156 tonne yr^{-1}). Compared to the averaged performance of "BMP-only" portfolios, the system benefit, corn production, soybean production of this specific "BMPs + EBTs" portfolio would be 18.4, 32.8, and 33.9% higher, respectively, while the P load would be 68.1% lower. In addition, the nitrate load of the specific "BMPs + EBTs" portfolio would be 40.5% higher than the averaged nitrate load of "BMP-only" portfolios due to the intensive BMP application and large LUC (19.0%). Moreover, as shown by the sensitivity analysis of the cost parameters, reducing the cost of EBTs can better improve the system performance than reducing the BMP cost (Table S8).

Figure 4b represents a more detailed multidimensional overall performance of solutions under "BMP-only" and "BMPs + EBTs" scenarios. Compared to the performance of the baseline (black dashed) that shows high trade-offs among the metrics, both "BMP-only" + "BMPs + EBTs" can mitigate trade-offs to some extent. However, poor performance still exists with "BMP-only" in some metrics such as P loads, crop production, total system benefit, and energy demand in WWT. This is because the "BMP-only" portfolio requires intensive BMP adoption and large land-use change (up to 25%), which significantly reduces the nitrate load but does little help to the P load at the outlet given that the majority of P comes from the point source. It is also worth noting that several metrics in BAU show better performance than "BMPs + ETBs" and "BMP-only", such as the system benefit and crop production. However, BAU does not meet the water quality improvement, which shows the nature of trade-offs. Overall, the "BMPs + EBTs" averaged portfolio (green color) shows a more balanced performance of the FEW systems as most dimensions are improved from the "BMP-only". For example, the P loads with "BMPs + EBTs" portfolios are significantly lower than that with the "BMP-only" portfolios, due to the significant point-source P reduction from EBTs. Meanwhile, the energy consumption of WWT with "BMPs + EBTs" portfolios is also lower due to decreased airflow demand attributed to denitrification in updated layouts (i.e., EBPR technology) than the status quo layout (i.e., activated sludge).[28] Crop production (including corn and soybean) and economic benefits (including the environment benefit) under "BMPs + EBTs" portfolios are also improved because the LUC to perennial grasses is much less, compared to "BMP-only". It is noted that some aspects with "BMPs + EBTs" portfolios perform worse than those with "BMP-only". For example, the energy consumption of DWT and nitrate loads under "BMPs + EBTs" are higher, because they do not apply intensive BMPs so that nitrate concentration in the Decatur Lake (where raw drinking water is taken) is higher.[9] However, those aspects in both portfolio groups perform better than the baseline.

It should be noted that there is no simple ranking of the importance of metrics. When it comes to select a specific watershed management portfolio, decisions should be made on agreed objective preferences in the context of multiple-criterion decision making (MCDM). This is, however, beyond the scope of this study. Another note is that nitrate concentrations occasionally exceed the MCL in Lake Decatur and raw drinking water, which is the most significant water quality problem for water supply in City of Decatur. This problem has been studied extensively and has been largely addressed in Decatur and elsewhere (e.g., Des Moines) by deploying nitrate removal technology in municipal water treatment. The cost data used in ITEEM are from the treatment plant provided by Sanitary District of Decatur (SDD). In addition, it has been well-recognized that tile drained watersheds are prone to "leak" nitrate, especially after a drought event that reduces corn yields.[44,45] This leakage can be reduced by the adoption of agricultural BMPs, as shown in our simulation results, which are basically consistent with previous studies.

ITEEM, a surrogate-based model, adopts a large number of parameters from several process models (SWAT, GPS-X, SuperPro). These models were well-calibrated before they were converted into surrogates.[28,30,33,42] Indeed, dealing with uncertainty transform in surrogating modeling[46] and uncertainty analysis of an integrated model involving many uncertain parameters from multiple process models[3,47] is challenging and presents a timely important research problem. Given that the main purpose of this paper is to search for the optimal choice of BMPs and EBTS at the watershed scale, we recognize that the uncertainty of the economic parameters, among all uncertain ITEEM variables, can have significant impact on the modeling results. Thus, we conduct sensitivity analysis on costs of BMPs and EBTs via four scenarios to investigate the cost effect of BMPs and EBTs; especially how the costs might impact synergies and trade-offs.

The sensitivity analysis sets ±20% cost parameter change from the baseline, based on our previous analysis[28,30,48] and historical cost data from Illinois Crop budgets,[49] which represents a reasonable variation range of the cost for BMPs and EBTs. As shown in Table S9, high BMP cost and low EBT cost can enhance the system benefit by 5.7%, while a low BMP cost and high EBT cost will reduce system benefit by 3.1%, indicating that lowering costs of EBTs would result in more system benefit. Lowering the costs of BMPs would encourage more applications of BMPs, which reduce the crop production by 12.5−23.3% and enhance the water quality by 10.0−11.7%. Regarding the impact on the system net benefit, it is found that BMPs and EBTs contribute 40 and 60% of system net benefit for the baseline, ending a benefit-cost ratio of 0.30; increasing BMP cost and reducing EBT cost will decrease the benefit-cost ratio to 0.17. However, reducing the BMP cost and increasing EBT cost will reduce the benefit-cost ratio to 0.21. Those results suggest that reducing the cost of EBTs is more needed than reducing the BMP cost.

IMPLICATIONS AND OUTLOOK

Integrated technology-environment-economics modeling demonstrates the feasibility of resolving the P paradox in Corn Belt watersheds via a pilot study of the USRW. The results show that the amount of P recovered from corn biorefinery (14 629 metric ton (MT) yr^{-1}) is more than 2 times the agronomic P requirement (6962 MT yr^{-1}) in the watershed. It is found that portfolios combining BMPs and EBTs (e.g., WWT, CB) can enhance the FEWS performance toward nutrient pollution reduction targets for NO_3−N and P, as compared to portfolios with BMP-only solutions. Our study highlights that engineering systems (e.g., wastewater treatment, corn biorefineries) along with agricultural BMPs not only have a critical role in meeting aggressive nutrient reduction targets (e.g., 45% nutrient load reduction) but also help enhance synergies and mitigate trade-offs of multidimension FEWS, compared to BMP-only solutions. In particular, it found that BMP-only portfolios need to include intensive LUC (i.e., 19% of agricultural land) to meet the P reduction goal in the agro-industry watershed. However, by coordinating with engineering technologies, LUC will be reduced to only 4%.

Our study also suggests future work opportunities. Importantly, the economic market of recovered P products can be complex, involving multiple stakeholders (e.g., government incentives, biorefineries, and farmers) and the impacts of using recovered P as fertilizer and coproducts on cattle merit further investigations.[29] We have to note that there is an institutional need for accommodating the real−real realization of the solutions recommended by the integrated modeling tool (ITEEM), which involves multiple stakeholders and multilevel of government agencies.[50] The key question is who is choosing the portfolios and doing the coordinated implementation? Experiences with urban−agricultural collaboration support the well-noted attribution of the issue as a "wicked problem".[51] Our study site, the USRW, has a history of promoting watershed-wide solution to maintain storage of the Decatur Lake, which is the source of drinking water for City of Decatur and food industrial water use. Sediment dredging has been used as an option of the very expensive measure;[52] City of Decatur has devised a long-term watershed management plan that includes stakeholder outreach and recommendations to implement BMPs for soil erosion control.[53] The issue addressed in the current study is more complex, since it brings in nutrient dischargers (i.e., food and ethanol processing plants) as a new stakeholders (or players), and institutional setting to coordinate the collaboration among farmers, industries, rural community leaders, and city and country agencies is needed to address the integrated solutions. The trade-off and synergy analysis among different portfolios can inform the collaboration. The modeling tool (ITEEM) and the analysis with the pilot watershed can be extended other watersheds in the Corn Belt and other regions to address the nutrient pollution reduction goals while enhancing food security by maintaining sufficient land for food crops and avoiding P deficit in soil by using recovered P as fertilizers), via cost-effective technologies and practices.

ASSOCIATED CONTENT

Data Availability Statement

Data sources supporting the results of this study can be found in the Supporting Information. Codes for running the integrated model with the optimization algorithm are available in GitHub: https://github.com/shaobinli/ITEEM.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c02055.

Details on the simulations and cost-effectiveness of agricultural best management practices, multiobjective formulations of ITEEM, and multi-dimensional outputs of food, energy, water systems (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the US National Science Foundation under the Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) (award number 1739788). We sincerely thank industrial, governmental, and agricultural stakeholders for providing valuable information on FEW systems of the testbed watershed. The findings and conclusions in this article are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

REFERENCES

(1) Kling, C. L.; Arritt, R. W.; Calhoun, G.; Keiser, D. A. Integrated Assessment Models of the Food, Energy, and Water Nexus: A Review and an Outline of Research Needs. *Annu. Rev. Resour. Econ.* **2017**, *9* (1), 143−163.

(2) Bleischwitz, R.; Spataru, C.; VanDeveer, S. D.; Obersteiner, M.; van der Voet, E.; Johnson, C.; Andrews-Speed, P.; Boersma, T.; Hoff, H.; van Vuuren, D. P. Resource Nexus Perspectives towards the United Nations Sustainable Development Goals. *Nat. Sustain.* **2018**, *1* (12), 737−743.

(3) Li, S.; Cai, X.; Emaminejad, S. A.; Juneja, A.; Niroula, S.; Oh, S.; Wallington, K.; Cusick, R. D.; Gramig, B. M.; John, S.; McIsaac, G. F.; Singh, V. Developing an Integrated Technology-Environment-Economics Model to Simulate Food-Energy-Water Systems in Corn Belt Watersheds. *Environ. Model. Softw.* **2021**, *143*, No. 105083.

(4) Cai, X.; Wallington, K.; Shafiee-Jood, M.; Marston, L. Understanding and Managing the Food-Energy-Water Nexus − Opportunities for Water Resources Research. *Adv. Water Resour.* **2018**, *111*, 259−273.

(5) Huntington, H. P.; Schmidt, J. I.; Loring, P. A.; Whitney, E.; Aggarwal, S.; Byrd, A. G.; Dev, S.; Dotson, A. D.; Huang, D.; Johnson, B.; Karenzi, J.; Penn, H. J. F.; Salmon, A. A.; Sambor, D. J.; Schnabel, W. E.; Wies, R. W.; Wilber, M. Applying the Food−Energy−Water Nexus Concept at the Local Scale. *Nat. Sustain.* **2021**, *4* (8), 672−679.

(6) Van Vuuren, D. P.; Bijl, D. L.; Bogaart, P.; Stehfest, E.; Biemans, H.; Dekker, S. C.; Doelman, J. C.; Gernaat, D. E. H. J.; Harmsen, M. Integrated Scenarios to Support Analysis of the Food-Energy-Water Nexus. *Nat. Sustain.* **2019**, *2*, 1132−1141.

(7) Housh, M.; Yaeger, M. A.; Cai, X.; Mcisaac, G. F.; Khanna, M.; Sivapalan, M.; Ouyang, Y.; Al-Qadi, I.; Jain, A. K. Managing Multiple Mandates: A System of Systems Model to Analyze Strategies for Producing Cellulosic Ethanol and Reducing Riverine Nitrate Loads in the Upper Mississippi River Basin. *Environ. Sci. Technol.* **2015**, *49* (19), 11932−11940.

(8) IEPA, IDOA, and University of Illinois Extension. Illinois Nutrient Loss Reduction Strategy. 2015, Illinois Environmental Protection Agency and Illinois Department of Agriculture; Springfield, Illinois. University of Illinois Extension; Urbana, Illinois. https://epa.illinois.gov/content/dam/soi/en/web/epa/documents/water-quality/watershed-management/nlrs/nlrs-final-revised-083115.pdf.

(9) Twomey, K. M.; Stillwell, A. S.; Webber, M. E. The Unintended Energy Impacts of Increased Nitrate Contamination from Biofuels Production. *J. Environ. Monit.* **2010**, *12* (1), 218−224.

(10) Smith, V. H.; Tilman, G. D.; Nekola, J. C. Eutrophication: Impacts of Excess Nutrient Inputs on Freshwater, Marine, and Terrestrial Ecosystems. *Environ. Pollut.* **1999**, *100* (1−3), 179−196.

(11) Paerl, H. W.; Otten, T. G.; Kudela, R. Mitigating the Expansion of Harmful Algal Blooms Across the Freshwater-to-Marine Continuum. *Environ. Sci. Technol.* **2018**, *52* (10), 5519−5529.

(12) Khanna, M. Nexus between Food, Energy and Ecosystem Services in the Mississippi River Basin: Policy Implications and Challenges. *CHOICES* **2017**, *32* (4), 1−9.

(13) D'Odorico, P.; Davis, K. F.; Rosa, L.; Carr, J. A.; Chiarelli, D.; Dell'Angelo, J.; Gephart, J.; MacDonald, G. K.; Seekell, D. A.; Suweis, S.; Rulli, M. C. The Global Food-Energy-Water Nexus. *Rev. Geophys.* **2018**, *56* (3), 456−531.

(14) Jarvie, H. P.; Sharpley, A. N.; Flaten, D.; Kleinman, P. J. A.; Jenkins, A.; Simmons, T. The Pivotal Role of Phosphorus in a Resilient Water-Energy-Food Security Nexus. *J. Environ. Qual.* **2015**, *44* (4), 1049−1062.

(15) Lougheed, T. Phosphorus Paradox: Scarcity and Overabundance of a Key Nutrient. *Environ. Health Perspect.* **2011**, *119* (5) .

(16) McIsaac, G. F.; Hodson, T. O.; Markus, M.; Bhattarai, R.; Kim, D. C. Spatial and Temporal Variations in Phosphorus Loads in the

Illinois River Basin, Illinois USA. *J. Am. Water Resour. Assoc.* **2022**, 1−16.
(17) Liang, S.; Qu, S.; Zhao, Q.; Zhang, X.; Daigger, G. T.; Newell, J. P.; Miller, S. A.; Johnson, J. X.; Love, N. G.; Zhang, L.; Yang, Z.; Xu, M. Quantifying the Urban Food-Energy-Water Nexus: The Case of the Detroit Metropolitan Area. *Environ. Sci. Technol.* **2019**, *53* (2), 779−788.
(18) Liang, Y.; Li, Y.; Liang, S.; Feng, C.; Xu, L.; Qi, J.; Yang, X.; Wang, Y.; Zhang, C.; Li, K.; Li, H.; Yang, Z. Quantifying Direct and Indirect Spatial Food − Energy − Water (FEW) Nexus in China. *Environ. Sci. Technol.* **2020**, *54*, 9791−9803.
(19) Ravar, Z.; Zahraie, B.; Sharifinejad, A.; Gozini, H.; Jafari, S. System Dynamics Modeling for Assessment of Water−Food−Energy Resources Security and Nexus in Gavkhuni Basin in Iran. *Ecol. Indic.* **2020**, *108*, No. 105682.
(20) Mitchell, J. K.; McIsaac, G. F.; Walker, S. E.; Hirschi, M. C. Nitrate in River and Subsurface Drainage Flows from an East Central Illinois Watershed. *Trans. ASAE* **2000**, *43* (2), 337−342.
(21) Carpenter, S. R. Phosphorus Control Is Critical to Mitigating Eutrophication. *PNAS* **2008**, *105*, 11039−11040.
(22) EPA Science Advisory Board. *Hypoxia in the Northern Gulf of Mexico: An Update by the EPA Science Advisory Board*; Washington, DC, 2007.
(23) Maringanti, C.; Chaubey, I.; Arabi, M.; Engel, B. Application of a Multi-Objective Optimization Method to Provide Least Cost Alternatives for NPS Pollution Control. *Environ. Manage.* **2011**, *48* (3), 448−461.
(24) Rao, N. S.; Easton, Z. M.; Schneiderman, E. M.; Zion, M. S.; Lee, D. R.; Steenhuis, T. S. Modeling Watershed-Scale Effectiveness of Agricultural Best Management Practices to Reduce Phosphorus Loading. *J. Environ. Manage.* **2009**, *90* (3), 1385−1395.
(25) Lemke, A. M.; Kirkham, K. G.; Lindenbaum, T. T.; Herbert, M. E.; Tear, T. H.; Perry, W. L.; Herkert, J. R. Evaluating Agricultural Best Management Practices in Tile-Drained Subwatersheds of the Mackinaw River, Illinois. *J. Environ. Qual.* **2011**, *40* (4), 1215−1228.
(26) Gaddis, E. J. B.; Voinov, A.; Seppelt, R.; Rizzo, D. M. Spatial Optimization of Best Management Practices to Attain Water Quality Targets. *Water Resour. Manag.* **2014**, *28* (6), 1485−1499.
(27) Cordell, D.; Drangert, J. O.; White, S. The Story of Phosphorus: Global Food Security and Food for Thought. *Glob. Environ. Chang.* **2009**, *19* (2), 292−305.
(28) Li, S.; Emaminejad, S. A.; Aguiar, S. E.; Furneaux, A. G.; Cai, X.; Cusick, R. Evaluating Long-Term Treatment Performance and Cost of Nutrient Removal at Water Resource Recovery Facilities under Stochastic Influent Characteristics Using Artificial Neural Networks as Surrogates for Plant-Wide Modeling. *ACS ES&T Eng.* **2021**, *1* (11), 1517−1529.
(29) Margenot, A.; Kitt, D.; Gramig, B. M.; Berkshire, T.; Chatterjee, N.; Hertzberger, A.; Aguiar, S.; Furneaux, A.; Sharma, N.; Cusick, R. D. Toward a Regional Phosphorus (Re)Cycle in the U.S. Midwest. *J. Environ. Qual.* **2019**, *48* (5), 1397−1413.
(30) Juneja, A.; Sharma, N.; Cusick, R.; Singh, V. Techno-Economic Feasibility of Phosphorus Recovery as a Coproduct from Corn Wet Milling Plants. *Cereal Chem.* **2019**, *96* (2), 380−390.
(31) Juneja, A.; Cusick, R.; Singh, V. Recovering Phosphorus as a Coproduct from Corn Dry Grind Plants: A Techno-economic Evaluation. *Cereal Chem.* **2020**, *97* (2), 449−458.
(32) Parthum, B.; Ando, A. W. Overlooked Benefits of Nutrient Reductions in the Mississippi River Basin. *Land Econ.* **2020**, *96* (4), 589.
(33) Li, S.; Wallington, K.; Niroula, S.; Cai, X. A Modified Response Matrix Method to Approximate SWAT for Computationally Intense Applications. *Environ. Model. Softw.* **2022**, *148*, No. 105269.
(34) H.R.6 - 110th Congress: Energy Independence and Security Act of 2007. https://www.congress.gov/bill/110th-congress/house-bill/6 (accessed Jan 29, 2020).
(35) University of Illinois Extension; IEPA; IDA. *Illinois Nutrient Loss Reduction Strategy: Biennial Report 2019*; 2019, https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/water-quality/watershed-management/excess-nutrients/documents/nlrs-biennial-report-2019-final.pdf.
(36) Deb, K.; Jain, H. An Evolutionary Many-Objective Optimization Algorithm Using Reference-Point-Based Nondominated Sorting Approach, Part I: Solving Problems with Box Constraints. *IEEE Trans. Evol. Comput.* **2014**, *18* (4), 577−601.
(37) Blank, J.; Deb, K. Pymoo: Multi-Objective Optimization in Python. *IEEE Access* **2020**, *8*, 89497−89509.
(38) US EPA. National Primary Drinking Water Regulations. https://www.epa.gov/sdwa/drinking-water-regulations-and-contaminants#Primary (accessed Aug 3, 2022).
(39) McIsaac, G. F.; Hu, X. Net N Input and Riverine N Export from Illinois Agricultural Watersheds with and without Extensive Tile Drainage. *Biogeochemistry* **2004**, *70* (2), 253−273.
(40) Vedachalam, S.; Mandelia, A.; Heath, E. A. *Source Water Quality and the Cost of Nitrate Treatment in the Mississippi River Basin*; Northeast-Midwest Institute Report; 2018.
(41) Burford, M. A.; Carey, C. C.; Hamilton, D. P.; Huisman, J.; Paerl, H. W.; Wood, S. A.; Wulff, A. Perspective: Advancing the Research Agenda for Improving Understanding of Cyanobacteria in a Future of Global Change. *Harmful Algae* **2020**, *91*, 101601.
(42) Niroula, S.; Wallington, K.; Cai, X. Addressing Data Challenges in Riverine Nutrient Load Modeling of an Intensively Managed Agro-Industrial Watershed. *J. Am. Water Resour. Assoc.* **2023**, *59* (2), 213−225.
(43) Broch, O. J.; Slagstad, D. Modelling Seasonal Growth and Composition of the Kelp Saccharina Latissima. *J. Appl. Phycol.* **2012**, *24* (4), 759−776.
(44) Gentry, L. E.; David, M. B.; Below, F. E.; Royer, T. V.; McIsaac, G. F. Nitrogen Mass Balance of a Tile-Drained Agricultural Watershed in East-Central Illinois. *J. Environ. Qual.* **2009**, *38* (5), 1841−1847.
(45) Lucey, K. J.; Goolsby, D. A. Effects of Climatic Variations over 11 Years on Nitrate-Nitrogen Concentrations in the Raccoon River, Iowa. *J. Environ. Qual.* **1993**, *22* (1), 38−46.
(46) Li, M.; Wang, Z. Surrogate Model Uncertainty Quantification for Reliability-Based Design Optimization. *Reliab. Eng. Syst. Saf.* **2019**, *192*, 106432.
(47) Little, J. C.; Hester, E. T.; Elsawah, S.; Filz, G. M.; Sandu, A.; Carey, C. C.; Iwanaga, T.; Jakeman, A. J. A Tiered, System-of-Systems Modeling Framework for Resolving Complex Socio-Environmental Policy Issues. *Environ. Model. Softw.* **2019**, *112*, 82−94.
(48) Gramig, B. M.; Reeling, C. J.; Cibin, R.; Chaubey, I. Environmental and Economic Trade-Offs in a Watershed When Using Corn Stover for Bioenergy. *Environ. Sci. Technol.* **2013**, *47* (4), 1784−1791.
(49) Schnitkey, G. *Revenue and Costs for Illinois Grain Crops, Actual for 2013 through 2018, Projected 2019 and 2020*; 2020.
(50) Wardropper, C. B.; Chang, C.; Rissman, A. R. Fragmented Water Quality Governance: Constraints to Spatial Targeting for Nutrient Reduction in a Midwestern USA Watershed. *Landsc. Urban Plan.* **2015**, *137*, 64−75.
(51) Lintern, A.; Mcphillips, L.; Winfrey, B.; Duncan, J.; Grady, C. Best Management Practices for Diffuse Nutrient Pollution: Wicked Problems Across Urban and Agricultural Watersheds. *Environ. Sci. Technol.* **2020**, 9159.
(52) City of Decatur. Lake Decatur Basins 1 through 4 Dredging Project Fact Sheet. https://www.decaturil.gov/wp-content/uploads/2016/11/Lake-Decatur-Dredging-Fact-Sheet.pdf (accessed Jan 30, 2023).
(53) Northwater Consulting. Lake Decatur Watershed Management Plan & Initiative. https://www.decaturil.gov/wp-content/uploads/2021/05/Long_Term_Strategy_30Apr2021.pdf (accessed Feb 10, 2023).

https://doi.org/10.1021/acs.est.3c02055
Environ. Sci. Technol. 2023, 57, 9194−9203