Greening America's Rivers: The Potential of Climate Financing for Nature-Based Water Quality Improvement

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August 10, 2023

Abstract

Nature-based solutions have been used to improve in-stream water quality in lieu of building electricity-consuming gray infrastructure. We propose that carbon financing can provide a potential novel incentive to accelerate this transition. Combining data on impaired waters, treatment technologies, and life cycle greenhouse gas emission accounting in the continental United States, we compare traditional gray treatment technologies to green technologies which include constructed wetlands, saturated buffers, and agricultural management practices. We show that across the contiguous United States, green alternatives are less expensive, less energy intensive, and less carbon intensive than gray infrastructure alternatives and could save \$15.6 billion USD, 21.7 terawatt-hours of electricity, and 29.8 million tonnes of CO2-equivalent emissions per year while sequestering over 4.2 million CO2e per year over a 40 year time horizon. While incentivizing adoption of green infrastructure remains challenging because of utility and regulator risk aversion, we find that the green solutions may have the potential to generate \$679 million annually in carbon credit revenue (at \$20/credit), which represents a unique opportunity to help institutionalize green solutions that meet the same water quality standards as gray infrastructure.

1 Introduction

Freshwater quality in the United States is impaired by non-point source pollution from land-use change, agricultural and forestry practices, soil erosion, and urbanization as well as large-scale, short-and-medium term shocks associated with wildfires and other impacts of climate change. A dominant form of water quality impairment is fertilizer application and subsequent runoff to streams [1]. The most prominent water quality impacts of fertilizer are harmful algae blooms and subsequent anoxic zones either in lakes or in near-coastal environments [2]. Point-source river discharges (i.e. wastewater treatment facilities) are regulated by the United States Environmental Protection Agency (EPA) and state agencies under the Clean Water Act, while non-point sources are largely unregulated. These environmental and regulatory realities are subsequently putting increasing pressure on water and wastewater utilities to address riverine water quality. Typically, water and wastewater utilities meet these regulatory obligations by constructing "gray infrastructure", such as secondary, tertiary and reverse osmosis treatment plants, requiring significant capital and operational costs as well as embodied emissions from materials and indirect emissions from energy use throughout their operational lifetimes. Water and wastewater treatment plants currently account for about 2% of energy use and 45 million tonnes of carbon dioxide equivalent (CO2e) emissions per year in the United States [3]. In many cases, gray infrastructure could be substituted with green infrastructure including riparian, floodplain, and wetlands restoration; regenerative agricultural practices; improved forestry management; and other efforts to reduce non-point source contamination to enable point dischargers to meet water quality standards. These types of formal, market-based 'water quality trading' programs were established and recently strengthened by the EPA [4, 5] and several state-level regulators, but have not achieved significant scale, despite often being much more cost effective [6, 7, 8], primarily because distributed, nature-based or green solutions are not as readily monitored and performance is not easily verified as established, gray infrastructure technology solutions.

This technology–capability barrier leads to risk adversity on the part of the regulator. In turn, utilities are unwilling to burden tax- and rate-payers with green infrastructure project costs if a required regulator-provided permit is not forthcoming. Emerging technologies may support improved monitoring and management of nature-based or green water quality solutions (e.g.[9, 10, 11, 12, 13, 14]). Paired with these advances, climate finance may provide a private capital source to motivate utilities and regulators using green infrastructure to take pre-permit, early action. In this light, one way to view climate finance mechanisms is that they offer the potential to redirect climate-damaging capital toward water infrastructure and create a sustainable, performance-based funding stream to move away from fossil-fuel dependent infrastructure. For this to hold the financing needs to occur in locations where the transition to renewables is slow, and where existing efforts to switch from energy intensive infrastructure to nature based solutions is lacking.

In this research, we evaluate the economic and environmental potential of nutrient trading programs. The economic and life-cycle greenhouse gas (GHG) emissions savings by using green wastewater treatment methods in place of gray wastewater treatment methods is evaluated. The primary analysis evaluates the benefits seen by nutrient (nitrogen and phosphorus) reduction. The US EPA defines five target effluent nutrient concentration levels for wastewater treatment technologies. Nutrient removal requirements vary state-by-state but have generally trended toward increased stringency, requiring water treatment plant technology upgrades and corresponding increases in energy demand [15, 16, 17]. Given this trend, we consider both Level 2 (removal of nitrogen to 8 mg/L and phosphorus to 1 mg/L) and Level 5 (removal of nitrogen to 2 mg/L and phosphorus to 0.02 mg/L) [15]. Geospatially resolved nutrient impaired water data is combined with the performance of various gray and green infrastructure alternatives to determine the total cost and environmental impact (GHG emissions) associated with various solutions to water quality targets. The discussion focuses on the potential impact of climate finance (carbon credits) to support the development and deployment of green infrastructure.

2 Results

The outcomes of the work are presented in three subsections: 1. nutrient treatment potential of green infrastructure, 2. global warming potential (GWP) of gray compared to green treatment technologies, and 3. total costs and climate finance potential for gray and green treatment technologies. A summary table of key results from this analysis are shown in Table 1.

2.1 Nutrient Remediation Potential of Green Infrastructure

In total, we find that 31.7% (530,255 tonnes N/yr) and 20.8% (54,110 tonnes P/yr) of the desired nitrogen and phosphorus treatment could be achieved using green infrastructure, for the Level 5 scenario (Figure 1). For the Level 2 scenario, 36.8% (403,913 tonnes N/yr) and 22.5% (39,453 tonnes P/yr) of the desired nitrogen and phosphorus treatment could be achieved using green infrastructure, respectively (Supplemental Figure 6). The primary reason why green treatment methods cannot achieve higher nutrient treatment loads is due to limited agricultural land in the waterbasins and limitations on geographic deployment. For example, saturated buffers and woodchip bioreactors can only be used in locations with tile drainage, but are also two of the treatment methods with the highest nutrient reduction effectiveness. Supplemental Figure 5 illustrates the effectiveness of each of the green treatment methods (and combinations of methods) at meeting desired nutrient treatment goals.

Table 1: Aggregated results for the national deployment of gray or green technologies to treat water to two different levels (Level 2 and Level 5)

	Level 2	**Level 5**
Treatment Target mg N/L	8	2
Treatment Target Limits mg P/L	1	0.02
Gray Electricity Use (Tera Wh/yr)	6.8	21.7
Gray Emissions (MtCO2e/Year)	11.9	29.8
Gray Cost ($B/Year)	$14.9	$28.5
Green Emissions (MtCO2e/Year)	-3.4	-4.2
Green Cost ($B/Year)	$10.0	$13.6
Net Emissions (MtCO2e/Year)	15.3	33.9
Carbon Revenue		
Total ($B/Year)	$0.3	$0.7
Green Net Savings w/ Carbon Revenue ($B/Year)	$5.2	$15.6
Mean Carbon Revenue vs Green Waterbasin Costs	5.4%	8.6%
StDev of Carbon Revenue vs Green Waterbasin Costs	5.7%	10.5%
Max Carbon Revenue vs Green Waterbasin Costs	20.9%	43.7%

A similar analysis was completed for the deployment of gray technologies. In order to ensure green and gray treatments were compared evenly, the gray nutrient treatment levels were set equal to those of the green maximum treatment technologies even though they are not limited by agricultural land constraints. If these limitations were not placed gray treatment technologies, they would treat more nutrients which would increase their treatment costs and emissions and exaggerate the benefit of green treatment methods. Results are presented for the minimum cost technology for both green and gray technologies. The minimum costs gray technologies were Anaerobic/Anoxic/Oxic for Level 2 and 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis for Level 5 treatment scenarios.

2.2 Global Warming Potential of Gray vs Green Infrastructure

Annually, we find that gray treatment technologies would emit 29.7 MtCO2e while green treatment technologies would sequester 4.2 MtCO2e for the Level 5 scenario (Figure 2). This results in a annual carbon credit potential of 33.9 MtCO2e. Our results also show that green treatment technologies have reduced emissions compared to gray treatment technologies in every waterbasin.

Depending on the optimal green treatment technologies used (Supplemental Figure 7), waterbasin green house gas emissions can be either positive or negative. When optimized for both minimum cost and maximum nutrient treatment, our results show that the primary green treatment technology to use in the Corn Belt is saturated buffers which has a positive GWP. Conversely, the primary treatment technologies to use in the western US are constructed wetlands, nutrient rate reduction, and no-till farming which all have a negative GWP and therefore allow the waterbasin to also have negative nutrient treatment GWP compared

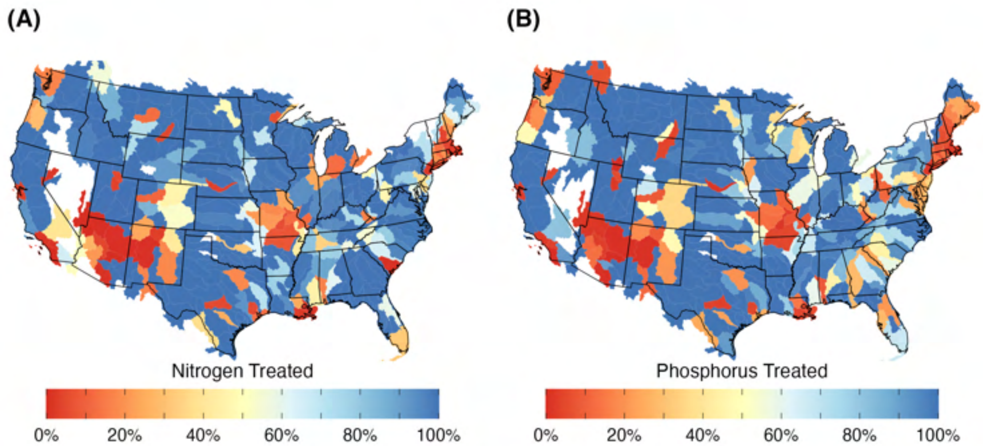


Figure 1: Percent of Nitrogen (A) and Phosphorus (B) treatment possible for green treatment technologies in each waterbasin for the Level 5 scenario of reducing mean nutrient concentrations to 2 mgN/L and 0.02 mgP/L. White space designates waterbasins which didn't have wastewater treatment facilities or didn't require nutrient treatment.

to conventional practices. Similar results were observed for the Level 2 scenario (Supplemental Figures 7 and 8). Gray treatment technologies emit 11.9 MtCO2e while green treatment technologies sequester 3.4 MtCO2e annually for the Level 2 scenario which results in a annual carbon credit potential of 15.3 MtCO2e. Overall, GWP values are reduced in the Level 2 scenario due to the reduction in nutrient treatment required.

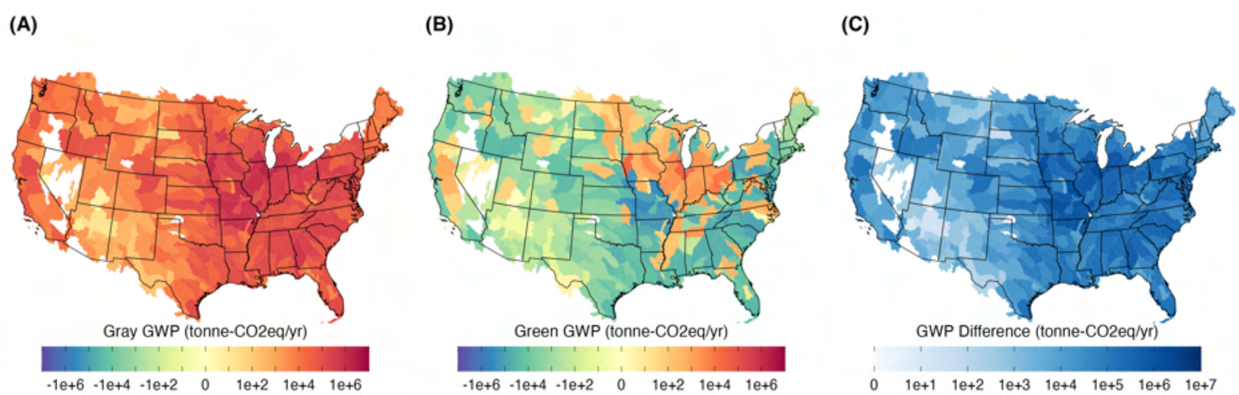


Figure 2: Continental United States global warming potential (GWP) in tonnes of CO2 equivalent emissions per year for removal of nitrogen (to 2 mg/L) and phosphorus (to 0.02 mg/L) using (A) gray treatment technologies (29.7 MtCO2e/year) and (B) green treatment technologies (-4.2 MtCO2e/year), and (C) net GWP representing potential carbon credit generation (33.9 MtCO2e/year). White space designates waterbasins which didn't have wastewater treatment facilities or didn't require nutrient treatment.

2.3 Carbon Financing Potential of Green Infrastructure

Nutrient treatment costs for the Level 5 scenario were found to be \$28.4B/year and \$13.6B/year for gray and green technologies, respectively, when costs are normalized over the life of the technology. Additionally, we found the carbon financing potential is \$679 M/yr assuming a carbon credit price of \$20/tonne-CO2eq which results in the total savings of green treatment technologies when compared to gray treatment and including carbon financing potential of \$15.6B/year (Figure 3). Contrary to the GWP results, green treatment technologies are not cheaper than gray treatment technologies in all waterbasins.

Of the 316 waterbasins in the CONUS which required nutrient treatment, 222 (70%) had green treatment costs cheaper than the gray treatment technologies excluding carbon financing revenues. If carbon financing revenue is added, 232 (73%) of waterbasins had green treatment costs cheaper than gray treatment technologies. However, when evaluated as a percent of total nutrients treated in the CONUS, 93.4% of nitrogen and 90.2% of phosphorus is treated in waterbasins where green treatment costs are cheaper than gray treatment technologies when carbon financing revenues are excluded. These values increase to 94.6% of nitrogen and 98.3% of phosphorus treated in the CONUS in waterbasins which green technologies are cheaper when carbon financing revenues are included. The primary driver for increased green treatment costs compared to gray technologies in some waterbasins is farmer incentive payments. These waterbasins are those where the optimum green treatment technology is land based (nutrient rate reduction, split nutrient application, cover crops, and no-till farming) which incurs annual farmer incentive payments, compared to the one-time farmer incentive payments for other green treatment methods. On a national level, farmer incentive payments make up 46% (\$6.2B/year) of the total green treatment costs in the Level 5 scenario.

Nutrient treatment costs for the Level 2 scenario were found to be \$14.9B/year and \$10.0B/year for gray and green technologies, respectively, when costs are normalized over the life of the technology. Additionally, we found the carbon financing potential is \$307 M/yr assuming a carbon credit price of \$20/tonne-CO2eq and a 40 year lifespan. This results in the total savings of green treatment technologies when compared to gray treatment and including carbon financing potential of \$5.2B/year (Supplemental Figure 9). Of the 316 waterbasins in the CONUS which required nutrient treatment, 168 (53%) had green treatment costs cheaper than those of the gray treatment technologies excluding carbon financing revenues. If carbon financing revenue is added, 174 (55%) of waterbasins had green treatment costs cheaper than gray treatment technologies. However, when evaluated as a percent of total nutrients treated in the CONUS, 80.9% of nitrogen and 66.2% of phosphorus is treated in waterbasins where green treatment costs are cheaper than gray treatment technologies when carbon financing revenues are excluded. These values increase to 85.6% of nitrogen and 95.4% of phosphorus treated in the CONUS in waterbasins which green technologies are cheaper when carbon financing revenues are included. Similar to the Level 5 scenario, green treatment costs were significantly impacted by the farmer incentive payments. On a national level, farmer incentive payments make up 49% ($4.9B/year) of the total green treatment costs.

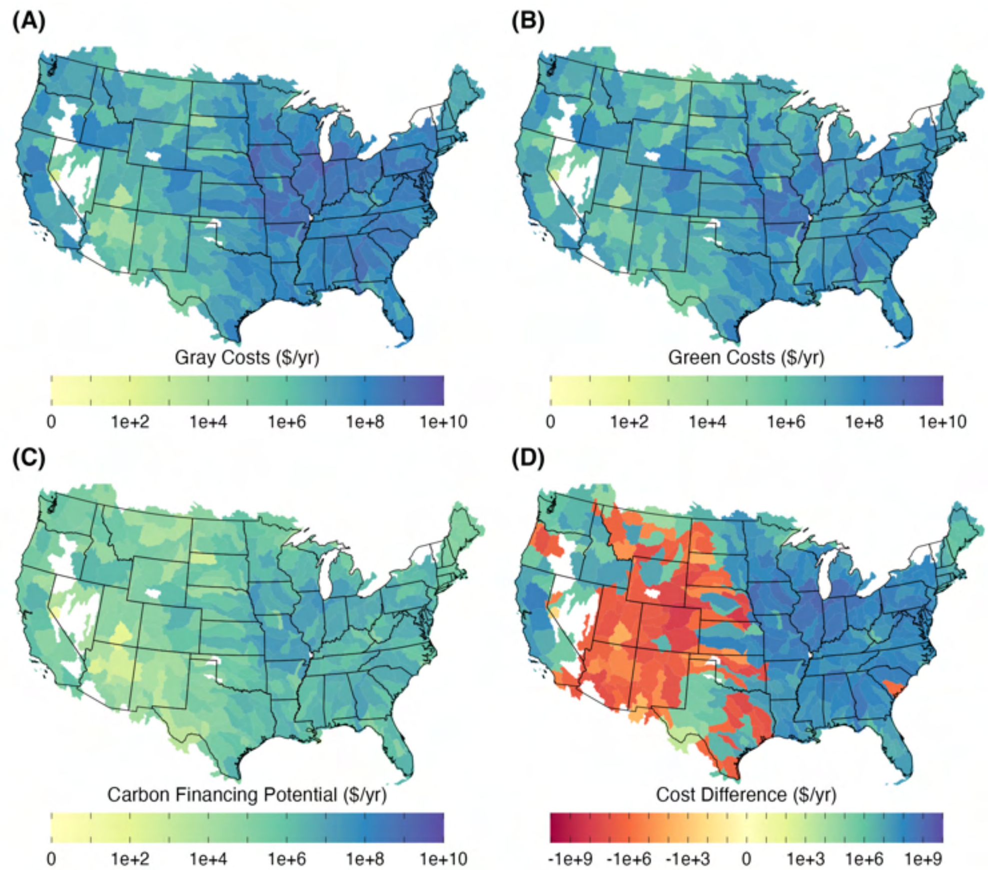


Figure 3: Continental United States water treatment costs for removal of nitrogen (to 2 mg/L) and phosphorus (to 0.02 mg/L) using (A) gray treatment technologies ($28.4B/year) and (B) green treatment technologies ($13.6B/year), (C) Potential carbon finance revenue ($676 M/year at $20/credit), and (D) net cost difference between gray and green treatment technologies when including carbon financing revenue ($15.6B/year). Negative cost differences show waterbasins where green technologies are more expensive than gray technologies. White space designates waterbasins which didn't have wastewater treatment facilities or didn't require nutrient treatment.

3 Discussion

River water quality improvements in the United States have been often delayed because of cost, complexity and litigation, with alternative compliance solutions, like nutrient trading, established but limited in scale. Meanwhile, carbon credits are designed to use market mechanisms to accelerate the energy transition. Combining this challenge and opportunity, there is a window of opportunity now to accelerate the improvement of America's rivers using these market mechanisms, as we transition to a renewable energy and restored watershed future.

Water and wastewater treatment in the United States already accounts for 2% of energy use and 45 million tonnes of CO2e emissions. We estimate these values could almost double over the coming years as utilities are obligated to increase treatment levels, even as states transition to renewable energy sources. Our results also indicate potential feasibility, effectiveness, and cost savings associated with green infrastructure alternatives to gray infrastructure to meet water quality goals and obligations. The EPA has recently revitalized their commitment to market-based water quality trading, emphasizing the role of the private sector in enabling improved river water quality in the United States, and encouraging regulators to embrace these opportunities and methodologies [5]. Yet, water quality trading programs in the United States have been limited in part by a reliance on regulator support, high transaction costs and a lack of pooled risk mitigation potential between programs. Fundamentally, local water problems have never benefited from a global, liquid economy. Carbon finance has been used extensively in the past fifteen years to deliver measurable clean drinking water services in low-income countries globally and could be applied in the United States to further motivate early, pre-permit green alternatives to meet water quality obligations [18].

International carbon credit markets are designed to financially incentivize early, voluntary action toward climate change mitigation, adaptation, and reduced emissions. Some estimates suggest that carbon credit markets can, "double climate ambition relative to current Paris pledges (NDCs) over 2020–2035, without increasing total costs," [19]. In 2022, some market research estimates that the volume of carbon credits in demand will increase at least 20x by 2035, with credits increasing in value from around $25 per tonne to a central estimate of $80-$150 per tonne by 2035 [20]. Toward this opportunity, new methodologies are needed which enable the generation of carbon credits, salable for revenue, associated with replacing gray infrastructure with green infrastructure to improve watershed health and river water quality. In this approach, the GHG emissions envisioned are avoided, rather than sequestered or removed, through the avoided construction of electricity consuming infrastructure. These avoided emissions, when achieved early and voluntarily, can have significant social benefits [21], while generating a potential $679 million annually in carbon credit revenue (at $20/credit), representing an opportunity to further motivate green solutions that meet the same water quality standards as gray infrastructure.

The results we've presented in this study are the best estimates possible with currently available data, but we acknowledge that some limitations exist with green nutrient technology research that should be addressed through future studies. Importantly the results and model presented here is not intended for top-down planning, it was developed to try and better understand the scope of the problem and opportunity. Any green infrastructure development must be done in a way that incorporates the local communities considerations, opportunities, values and rights. Critically however, the business as usual gray infrastructure creates inequalities in clean water access in the United States, often failing to serve the most disadvantaged populations without access to the best facilities. As such green infrastructure, if done right, offers a opportunity to ensure clean water is offered to a much wider portion of the population.

Limited data exists on the current prevalence and effectiveness of green technologies across the US. Existing research on these technologies is focused in the Midwestern US (i.e. Corn Belt) and non-point source nutrient treatment methods have a wide range of nutrient reduction efficiencies based on geographic location, agricultural techniques used, and local climate patterns. Studies need to be performed on each of the green treatment methods to evaluate their effectiveness elsewhere in the US. Surveys should also be completed to provide better estimates of the current prevalence of these technologies throughout the US to better estimate future potential. USDA census data is available for cover cropping and no-till farming across the US, but limited data is available for saturated buffers, woodchip bioreactors, constructed wetlands, and smart fertilizer application strategies. Literature shows that green treatment methods can be used in combination with each other, but it is unknown how the benefits of these technologies compound. Research should be performed to evaluate the effectiveness of these technologies when used in combination with each other to ensure nutrient treatment isn't saturated and to maximize the nutrient reduction of the technologies being implemented. The LCA estimates made for green technologies in this study should also be evaluated in specific case studies to capture nuances of the local installations and performance data should be used to accurately determine the GHG emissions. Additionally, it is important to acknowledge the evolution of the grid in terms of carbon emissions will impact the carbon financing potential of green nutrient treatment technologies. As the grid evolves with less environmental impact, carbon credits generated by offsetting gray infrastructure with green infrastructure will be reduced, which mean that the window of opportunity for leveraging carbon markets to incentivize a shift from gray to green infrastructure may be limited.

4 Methods

This study evaluates the economics and emissions of water treatment technologies in the CONUS. The CONUS was divided into smaller sections as designated by the United States Geological Survey's (USGS's) Hydrological Unit Code (HUC) regions. To maximize geographic resolution of this analysis, HUC 12 sub-watersheds were used wherever possible. However, it was assumed that nutrient trading could take place at the HUC 6 waterbasin level and, therefore, all results were aggregated to the waterbasin level [22]. Geodatabase files for various HUC regions were downloaded from the USGS's Watershed Boundary Dataset (WBD) [23]. Data associated with HUC 12 sub-watersheds was aggregated from United States Environmental Protection Agency's (EPA's) EnviroAtlas database [24]. EnviroAtlas provides national data layers at the

HUC 12 sub-watershed level with many of these data layers being derived from data with a resolution of 30 m. Full details of which data was required is discussed in each subsection. It was assumed that nutrient trading could take place within each waterbasin (HUC 6), therefore stricter requirements placed on existing facilities could only be satisfied by gray or green treatment methods within the same waterbasin.

4.1 Wastewater Nutrient Data

Geographically resolved nutrient loading data compared to water quality targets for point source dischargers in the CONUS motivates the water treatment trade study. Therefore, 2022 data from the Nutrient Model (Hypoxia Task Force Search) created by the EPA was used [25]. This data is provided through the EPA's Water Pollutant Loading Tool [26]. The Nutrient Model was created by EPA to provide access to aggregated nitrogen and phosphorus loads (including modeled loads) for facilities across the US. As such, data is provided for wastewater treatment facilities with current EPA National Pollutant Discharge Elimination System (NPDES) permits with facility information, total annual wastewater flow, total nutrient loads, and maximum allowable nutrient loads (if applicable). In total, 53,055 data entries were provided for 29,335 unique facilities. Data consists of both discharge monitoring report (28,318) and modeled (24,737) nutrient loads for both nitrogen (27,238) and phosphorus (25,817). Additionally, each data point was associated with a HUC 12 sub-watershed code so analysis could be evaluated on a geospatially resolved level. An overview of the input data including number of facilities, mean daily wastewater flow, mean nitrogen concentration, and mean phosphorus all aggregated to the waterbasin level can be viewed in Figure 4. For analysis of all technologies in this study, a 40 year time horizon was assumed.

4.2 Gray Treatment Methods

Gray nutrient treatment technologies outlined in the EPA's report title *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* were used in this analysis [15]. The EPA report estimated the costs and GWP of 8 alternative wastewater treatment technologies to treat excess nitrogen and phosphorus in wastewater streams. Costs and GWP were also provided for a 9th 'baseline' technology, but it was excluded from this analysis because its primary design was not focused on nutrient removal and had low nutrient remediation potential. Details of the gray treatment methods can be seen in Table 2. Each gray nutrient treatment technology was assigned a treatment level in the EPA report. These levels range from Level 2 to Level 5 based on their ability to achieve target effluent nutrient concentrations. These concentration levels are $8mgN/L$ and $1mgP/L$ for Level 2, $4-8mgN/L$ and $0.1-0.3mgP/L$ for Level 3, $3mgN/L$ and $0.1mgP/L$ for Level 4, and $< 2mgN/L$ and $< 0.02mgP/L$ for Level 5. Level 1 designates

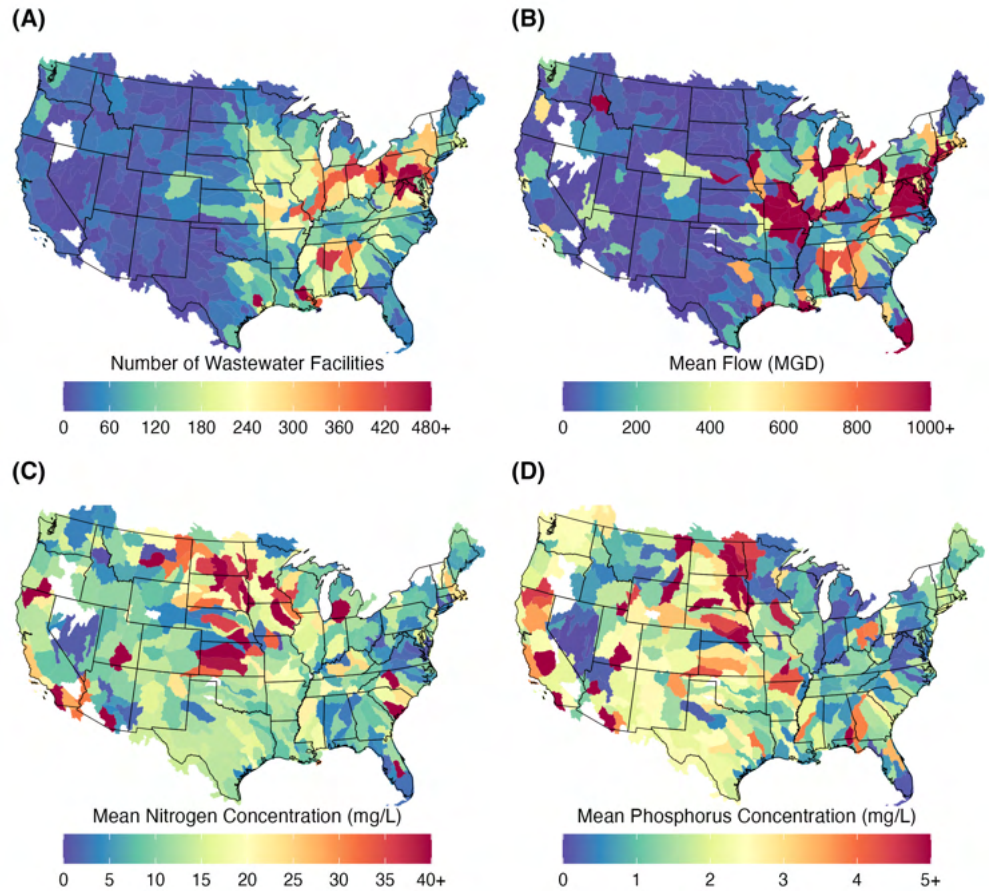


Figure 4: Wastewater treatment facility data in the contiguous United States: (A) Number of wastewater facilities in each waterbasin (B) Total mean flow in millions of gallons per day in each waterbasin (C) Mean Nitrogen concentration of the wastewater (mg/L) in each waterbasin (D) Mean Phosphorus concentration of the wastewater (mg/L) in each waterbasin.

that no effluent concentration is specified and has been excluded from this analysis accordingly.

To perform a geographically resolved analysis, costs and GWP of each gray treatment technology were adjusted based on the location of the facility being evaluated. For gray treatment technologies, only the electricity grid mix was assumed to vary geographically. Treatment costs and GWP presented in the EPA report assumed the 2010 US average electrical grid mix was used for water treatment and all cost information was presented in 2014 dollars. We assumed a linear increase in energy demand between Level 2 and Level 5, which is likely conservative as some estimates suggest an exponential increase in energy use approaching Level 5 [27]. Electricity prices were updated using the mean state electricity prices as reported by the US Energy Information Administration's (EIA) 2021 Annual Energy Outlook, which is the most recent annual outlook available [28]. To approximate the emissions associated with electricity use in various geographic regions in the US, the US EPA's Emissions & Generation Resource Integrated Database (eGRID) was used [29]. Since EIA electricity prices and eGRID mixes are not aggregated to the sub-watershed level, the GeoPandas library

Table 2: Costs and Emissions of Gray Treatment Methods. Treatment "Level" refers to the EPA's target effluent nutrient concentration levels for wastewater treatment technologies.

Name	***Abbr.***	***Level***	***N Cost (2022$/kgN)***	***P Cost (2022$/kgP)***	***N GWP (kg-CO2eq/kgN)***	***P GWP (kg-CO2eq/kgP)***	***N Removal (mg/L)***	***P Removal (mg/L)***
Anaerobic/Anoxic/Oxic	A2O	2	$ 28.59	$ 194.64	24.06	163.83	32	4.7
Activated Sludge, 3-Sludge System	AS3	2	$ 46.36	$ 370.86	28.75	230.00	32	4.0
5-Stage Bardenpho	B5	3	$ 30.54	$ 216.34	29.41	208.33	34	4.8
Modified University of Cape Town Process	MUCT	3	$ 31.27	$ 221.49	28.24	200.00	34	4.8
5-Stage Bardenpho with Denitrification Filter	B5/Denit	4	$ 31.41	$ 237.15	29.73	224.49	37	4.9
4-Stage Bardenpho Membrane Bioreactor	MBR	4	$ 29.74	$ 224.54	29.73	224.49	37	4.9
5-Stage Bardenpho with Sidestream Reverse Osmosis	B5/RO	5	$ 44.38	$ 346.14	46.15	360.00	39	5.0
5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis	MBR/RO	5	$ 42.29	$ 321.41	47.37	360.00	38	5.0

in Python was used to compare the shapefiles for US states and eGRID regions to HUC 12 sub-watersheds [30]. If two states or eGRID regions overlapped a sub-watershed region, the state or eGRID region which overlapped a larger area of the sub-watershed was assigned to the sub-watershed. All technology costs and electricity prices were converted to 2022 dollars using historical Consumer Price Index (CPI) data provided by the US Bureau of Labor Statistics using the mean annual CPI values for all items and the US city average was used [31, 32]. The electricity prices and GWP was updated for each gray treatment method in each HUC region using the total electricity demand (kWh/m^3) presented in the EPA report and 2021 electricity values using Equation 1:

$$X_{i,w} = X_{i,US} - ElectricDemand_i * Y_{US} + ElectricDemand_i * Y_w \tag{1}$$

where X represents the technology's cost or GWP, i represents the gray technology method, w represents the waterbasin value, US represents the United States mean value, $ElectricDemand$ represents electricity demand of nutrient treatment for each gray technology, and Y represents the geographic specific cost or GWP of electricity.

4.3 Green Treatment Methods

Green non-point source nutrient treatment methods range from minimally invasive nutrient fertilizer reduction to land altering constructed wetlands [33, 34]. For this analysis, 7 green treatment methods were considered, all of which are implemented on agricultural farmland (Table 3). These include 3 barrier treatment methods which are applied at the edge of the field (saturated buffers, woodchip bioreactors, and constructed wetlands) and 4 land treatment methods (nutrient rate reduction, split nutrient application, cover crops, and no-till farming). Some of these treatment methods treat both nitrogen and phosphorus, while others only treat one of the two nutrients considered. Mean nutrient removal percentages and treatment costs came from the 2016 *Illinois Nutrient Loss Reduction Strategy* report [34]. All values used within this analysis fall within the range of values reported in the literature [33, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46].

One limitation to published values on green treatment methods is that they are presented in terms of the cost for the farmer to implement the technology, not the costs that would be incurred by a utility encouraging the adoption of these technologies to avoid new gray infrastructure upgrades. Therefore, some of the technology costs (i.e. applied nutrient reduction and no-till farming) are negative because they are cheaper than conventional farming practices. Since this analysis was performed from the utilities perspective, it was assumed that the utility would incur the costs of technology adoption, but would not claim the benefits of cost saving practices. Therefore, it was assumed that the technology costs of the negative cost technologies would be zero.

Additionally, it was assumed that farmers would need to be financially incentivized by the utility to implement green nutrient treatment methods. Therefore, it was assumed that the utility would pay farmers $31/acre-yr for land treated with green treatment methods, which is the mean value reportedly paid to farmers in 2021 by the Soil and Water Outcomes Fund [47]. This incentive payment is in addition to the green technology costs paid for by the utility. Barrier treatment methods which only need to be installed once, were only assumed to pay incentive fees during the first year of operation. Land treatment methods are applied yearly and, as such, the incentive fees were paid out annually. Lastly, constructed wetlands require up to 6% of the treated farmland acres to be converted to a wetland [33]. As a conservative estimate, it was assumed that this land was productive farmland and the utility would need to rent the land from the farmer at the mean land rental prices as reported by the United States Department of Agriculture's (USDA's) 2022 land cash rental prices in order to compensate farmers for reducing their farm size [48]. Farmland rental prices were reported at a state level and were applied to each waterbasin based on the states which the waterbasin resided in. If the waterbasin covered land in multiple states, the land rental prices were calculated using a weighted mean based on the number of agricultural acres in each state. Land rental prices were assumed to stay constant over the life of the project.

Similar to the costs of gray treatment technologies, the costs of green treatment technologies were received in 2016 dollars and were converted to 2022 dollars using historical CPI data provided by the US Bureau of Labor Statistics [31, 32]. The GWP of each green treatment method were estimated using life-cycle inventory data from the EcoInvent 3.71 database, using cut-off analysis, accessed through the software openLCA 1.10.3 (https://openlca.org), and calculated using the Traci 2.1 impact assessment methodology [49, 50]. The GWP estimate for constructed wetlands includes direct land use change effects which were calculated using IPCC methodology [51]. Details of LCA calculations for each treatment method are provided in the Supplemental Information.

Since each green nutrient treatment method requires different topology, infrastructure, or climate in order to be implemented; not every green treatment method could be applied in every waterbasin. Therefore,

Table 3: Costs and Emissions of Green Treatment Methods. Treatment "Type" designates if the green treatment method is applied at the edge of the field (Barrier) or applied across the entire farm (Land).

Name	***Abbr.***	***Type***	***N Cost (2022\$/kgN)***	***P Cost (2022\$/kgP)***	***N GWP (kg-CO2eq/kgN)***	***P GWP (kg-CO2eq/kgP)***	***N Removal (%)***	***P Removal (%)***
Saturated Buffers	BU	Barrier	\$ 1.95	\$ 14.63	0.10	3.98	90%	50%
Woodchip Bioreactors	BR	Barrier	\$ 2.68	\$ -	0.70	-	25%	0%
Constructed Wetland	W	Barrier	\$ 4.88	\$ -	(3.90)	-	50%	0%
N Rate Reduction	NR	Land	\$ 0.00	\$ 0.00	(9.21)	(105.72)	10%	7%
Split N Application	NS	Land	\$ 7.56	\$ -	11.10	-	10%	0%
Cover Crop	CC	Land	\$ 3.90	\$ 158.52	0.55	8.10	30%	30%
No-till	NT	Land	\$ -	\$ 0.00	-	(91.35)	0%	50%

land limitations were added to green infrastructure on a waterbasin basis. These land limitations included the availability of tile-drained soil (saturated buffers and woodchip bioreactors), the availability of riparian buffer between agricultural land and discharge waterways (saturated buffers), the soil and climate to support wetlands (constructed wetlands), and the requirement of supplemental fertilizer application (nutrient rate reduction and split nutrient application). It was assumed that if the requirements were met in one part of the waterbasin, the requirements could be implemented in the rest of the waterbasin and the nutrient reduction strategy could be applied. For example, if tile drains were used on agricultural land in one part of the waterbasin, it was assumed that they could be added to all agricultural land in the waterbasin. Data for tile drain locations was acquired from Nakagaki et al. (2016) based on analysis from Sugg (2007) and data for riparian buffers, wetlands, and fertilizer application were acquired from the EPA's EnvironAtlas [52, 53, 24]. Details of each green treatment method's requirements is provided in Supplemental Information Table 4 and maps of tile drainage, riparian buffers, wetlands, and fertilizer application availability in each waterbasin is presented in Supplemental Information Figure 12.

One of the benefits of green nutrient treatment methods is that they can be used in combination with each other [33]. This analysis considered all combinations of the 7 treatment methods proposed. Since each of the barrier treatment methods are applied at the edge of the field before discharge to the waterway, it was assumed that only one barrier treatment method could be used at a time. Conversely, no limitations were placed on the land treatment methods. Therefore, 63 unique combinations of green treatment methods were evaluated to find the best performing treatment methods in each watershed. For combined green treatment methods, it was assumed that costs, GWP, and nutrient removal efficiency were compounded. For example, if saturated buffers were combined with cover crops, their nitrogen cost would be $\$1.95/kgN + \$3.90/kgN = \$5.85/kgN$, nitrogen GWP would be $0.10kg - CO_{2eq}/kgN + 0.55kg - CO_{2eq}/kgN = 0.65kg - CO_{2eq}/kgN$, and their nitrogen removal efficiency would be $90\% + 30\% * (100\% - 90\%) = 93\%$.

4.4 Calculation Methods and Assumptions

In order to estimate the nutrient trading potential of green versus gray nutrient reduction technologies, two scenarios were assumed. The first scenario assumed that each of the wastewater treatment facilities evaluated were required to meet Level 2 nitrogen and phosphorus concentration limits of $8mgN/L$ and $1mgP/L$, respectively. These values were selected because they are the conservative limit that all gray treatment technologies can achieve based on their treatment level in the EPA report. The second scenario assumed that each of the wastewater treatment facilities evaluated were required to meet Level 5 nitrogen and phosphorus concentration limits of $2mgN/L$ and $0.02mgP/L$, respectively. These values were selected because they are the limit that the advanced reverse osmosis gray treatment technologies can achieve based on their treatment level in the EPA report. Each scenario was evaluated independently of each other. For all treatment methods, analysis was performed on the facility level and nutrient trading was assumed to occur within each waterbasin.

For each scenario, all facilities where both nitrogen and phosphorus concentrations were lower than the specified limits were excluded from analysis. Additionally, each gray nutrient treatment technology had maximum concentration limits which they could decrease the effluent during treatment. It was assumed that the wastewater could be treated multiple times when the concentration was above this limit, but costs and GWP would increase by the multiple of the number of treatments required. To avoid the highest concentration scenarios which would significantly exaggerate the gray treatment costs, facilities which required a mean nutrient concentration reduction greater than 5X the Level 2 treatable concentration limit were excluded from analysis. Facilities located outside CONUS (i.e. Alaska, Hawaii, Puerto Rico, Guam, US Virgin Islands, and American Samoa) were also excluded due to their lack of HUC 12 sub-watershed data provided by the EPA's EnviroAtlas [24]. After data filtration to remove facilities residing outside the CONUS or with nutrient concentrations lower than treatable limits, 18,534 unique facilities remained for the Level 2 analysis (16,743 facilities treated for nitrogen, 14,499 facilities treated for phosphorus, and 12,708 facilities treated for both) and 22,386 unique facilities remained for the Level 5 analysis (19,807 facilities treated for nitrogen, 20,829 facilities treated for phosphorus, and 18,250 facilities treated for both).

In addition to gray treatment facility limitations, green treatment methods were limited by agricultural land availability within each waterbasin. Total area within each sub-watershed was calculated using the GeoPanda's area function in Python. The percentage of crop land and pasture land in each sub-watershed as reported by EnviroAtlas were used to approximate the total agricultural land in each sub-watershed [24]. Since nutrient trading was performed at the waterbasin level, sub-watershed values were aggregated to the waterbasin level to determine the maximum nutrient treatment of the waterbasin as a whole.

Additionally, some of the green treatment methods considered are already in use on farms throughout the CONUS, but limited information exists on their prevalence. The USDA's 2017 agricultural census provides state-level tillage and cover crop data, but geographically resolved data is unavailable for the other green treatment methods [54]. The most recent non-census data coverage data is provided by the Iowa Department of Agriculture and Land Stewardship in their *Iowa Nutrient Reduction Strategy 2018-19 Annual Progress Report* [43]. The report states that of the total 30,600,000 acres of farm land in Iowa, 8,200,000 acres (26.8%) were no-till farmed, 5,700,000 acres (18.6%) were treated with nutrient management strategies (nitrogen rate reduction and split nitrogen applications), 973,000 acres (3.2%) used cover cropping, 107,000 acres (0.35%) were treated with wetlands, and 2,000 acres (0.35%) were treated with either saturated buffers or woodchip bioreactors [43, 55]. To fill the gaps between the USDA census data and treatment methods considered, these values were applied to their respective green treatment methods across all waterbasins in the CONUS to provide a conservative estimate of land availability for additional green treatment applications. While accounting for land limitations, the maximum nutrient treatment potential of each green technology in each waterbasin was calculated using Equation 2:

$$NT_{i,w} = A_w * (Pct_{crop,w} + Pct_{past,w}) * (1 - Pct_{tech,i}) * N_{mean-loss,w} * Pct_{N-removal,i} \tag{2}$$

where $NT_{i,w}$ represents the possible nutrient treatment for each green technology (subscript i) in each waterbasin (subscript w), A_w represents the waterbasin total area, $Pct_{crop,w}$ represents the percent of waterbasin area which is crop land, $Pct_{pasture,w}$ represents the percent of waterbasin area which is pasture land, $Pct_{tech,i}$ represents the percent of agricultural land currently treated with each green treatment method, $N_{mean-loss}$ represents the mean nutrient loss per land area of agricultural land in the waterbasin, and $Pct_{N-removal,i}$ represents the percent of nutrient removal for each green technology. The state-level nutrient runoff values as predicted by the 2012 regional United States Geological Survey's Spatially Referenced Regression On Watershed attributes (SPARROW) models were used to quantify nutrient loading from agricultural land in each waterbasin [56, 57, 58, 59, 60, 61].

Analysis was performed first for all green treatment methods and combinations. The required nutrient treatment and the possible nutrient treatment were calculated on a waterbasin level as described in the previous paragraphs. If the available agricultural land in a waterbasin could not support the removal of the required nutrient load to meet the desired concentration limits, it was assumed that the maximum possible treatment would be applied based on the land available. The percentage of maximum nutrient treatment compared to the desired nutrient treatment was calculated and was used for nutrient treatment of all facilities within the waterbasin. Total land area required for nutrient remediation was also recorded to calculate farmer incentive payments. After the nutrient treatment loads were calculated for each wastewater facility, the new mean nutrient concentrations were calculated based on annual wastewater discharge. After final nutrient treatment loads were determined, the treatment costs (including farmer incentive and wetland costs) and GWP were calculated for both nutrients. Lastly, if both nitrogen and phosphorus were being treated, the total treatment costs and GWP of the facility were set by the nutrient which required more infrastructure. For example, if nitrogen required 500 ha of treatment to meet concentration limits and phosphorus required 1,000 ha, the phosphorus treatment costs and GWP were assumed for treatment of both nutrients at the facility since both nutrients can be treated simultaneously for certain treatment methods. Comparison of the nutrient treatment levels for each green treatment method are presented in the Supplemental Information.

After treatment costs and GWP were calculated for every wastewater treatment facility and each green treatment method (including combinations), an optimization was run to determine the maximum amount of nutrients that could be treated using green treatment methods in each waterbasin. In many waterbasins, multiple green treatment methods could treat the required nutrient load to reach the desired concentration limits. Therefore, a secondary optimization was performed to determine the minimum cost scenario and minimum GWP scenario when the maximum amount of nutrients were treated. Results for the minimum cost scenario are used for comparison to the gray treatment methods in the results section. The minimum GWP was excluded from the primary results section because it has a breakeven carbon cost of $\$939/tonne - CO_{2eq}$ when compared to the minimum cost scenario which is more expensive than direct air carbon capture technologies [62]. Detailed results for both optimization scenarios is shown in the Supplemental Information section.

Once costs and GWP were determined for each green treatment method, costs and GWP were calculated for each of the gray treatment methods. In order to ensure green and gray treatments were compared evenly, the gray nutrient treatment levels were set equal to those of the green maximum treatment scenarios even though they are not limited by agricultural land constraints. If these limitations were not placed gray treatment technologies, they would treat more nutrients than the green treatment methods which would increase their treatment costs and emissions and exaggerate the benefit of green treatment methods. Costs for all treatment methods were originally calculated at the wastewater facility level using sub-watershed characteristics. For analysis purposes, results were aggregated from the facility level to the waterbasin level.

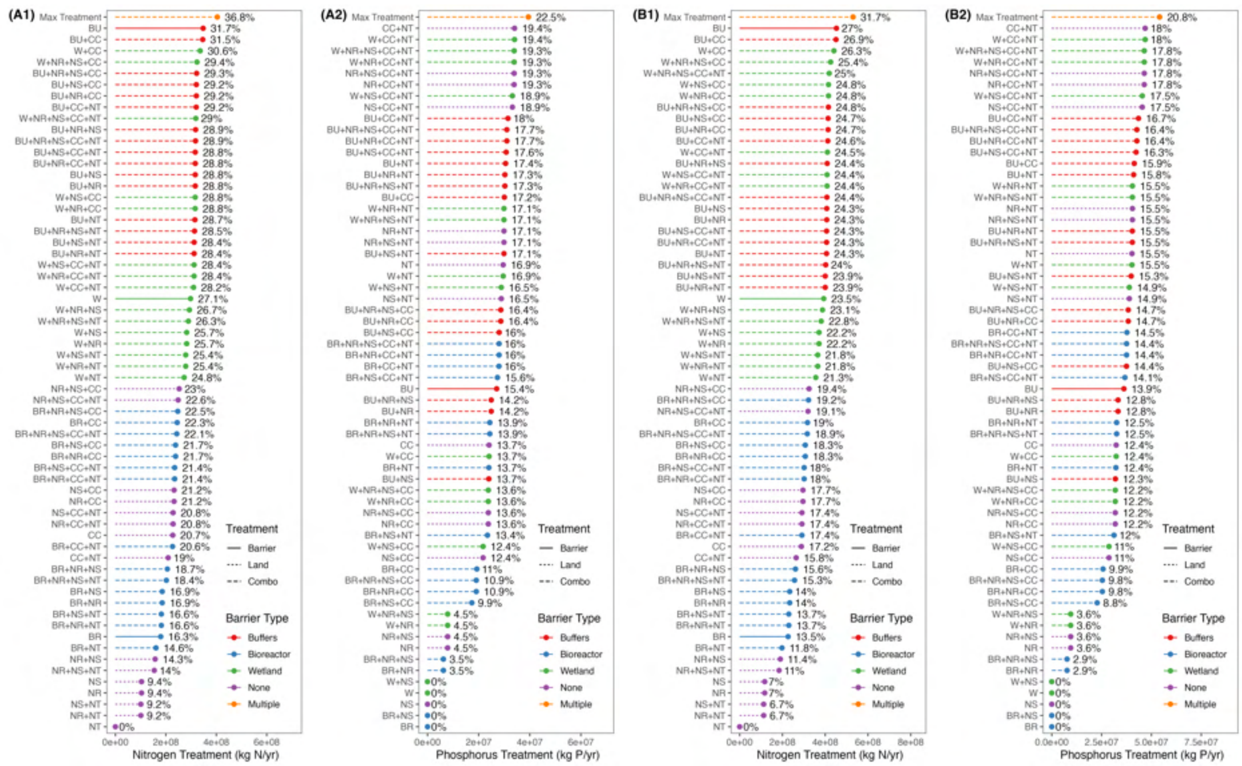
5 Supplemental Information

Additional methods and results are presented in this Supplemental Information section. Six subsections are included. The first subsection provides details on the total nutrient loads that green treatment technologies can achieve in the US. The second subsection details the optimum green infrastructure deployment across the contiguous United States (CONUS). The third subsection provides the results for the global warming potential (GWP) of gray and green treatment technologies across the CONUS. The fourth subsection details the total costs for gray and green technologies across the CONUS along with maps for carbon financing potential considering a $\$20/tonne - CO_{2eq}$ carbon credit price and the net different between the costs of each technology if carbon financing is included. The fifth nutrient subsection provides a comparison between the minimum cost and minimum emission green treatment scenarios verses grey treatment technologies. The sixth subsection provides additional details on the methods used for this analysis. The seventh subsection provides additional details on the assumptions used for green treatment methods LCA estimates.

5.1 Nutrient Remediation Potential of Green Infrastructure

This analysis considers 7 primary green nutrient remediation methods, all of which are implemented on agricultural farmland. These include 3 barrier treatment methods which are applied at the edge of the field (saturated buffers, woodchip bioreactors, and constructed wetlands) and 4 land treatment methods (nutrient rate reduction, split nutrient application, cover crops, and no-till farming). Additionally, combinations of the green treatment methods were also considered which resulted in 63 unique combinations of green treatment methods being evaluated. Each green nutrient treatment method had unique infrastructure requirements, agricultural land limitations, and nutrient removal efficiencies. Therefore, each green treatment method could treat different quantities of nitrogen and/or phosphorus. Maps of the nutrient treatment percentage in each waterbasin can be seen in Supplemental Figure 6 for the Level 2 scenario and in Figure 1 for the Level 5 scenario.

Supplemental Figure 5 illustrates the total nutrient treatment which each green treatment method, or combination of methods, could achieve for the Level 2 scenario (A) and Level 5 scenario (B). Also provided is the maximum treatment potential of green treatment methods if the most productive treatment method is selected in each waterbasin and the percent of the required nutrient treatment necessary to achieve desired nutrient concentration goals in the CONUS. In total, 31.7% (530,255 tonnes N/yr) and 20.8% (54,110 tonnes P/yr) of the desired nitrogen and phosphorus treatment could be achieved using green infrastructure, respectively, for the Level 5 scenario. For the Level 2 scenario, 36.8% (403,913 tonnes N/yr) and 22.5% (39,453 tonnes P/yr) of the desired nitrogen and phosphorus treatment could be achieved using green infrastructure, respectively. The primary reason why green treatment methods cannot achieve higher nutrient treatment loads is due to limited agricultural land in the watershed, low nutrient removal efficiencies (which results in large land requirements), and limitations on geographic deployment (i.e., saturated buffers and woodchip bioreactors can only be used in locations with tile drainage which is predominately used in the corn belt, but not elsewhere in the US). This can be seen in Supplemental Figure 5 because the treatment methods with high nutrient removal efficiencies and limited geographic constraints tend to remove the most nutrients (constructed wetland + cover crops for nitrogen and all land treatment methods for phosphorus).



(a) Level 2 Treatment

(b) Level 5 Treatment

Figure 5: Maximum Nitrogen (1) and Phosphorus (2) treatment capacity of each green treatment technology or combinations of green technologies for the Level 2 (A) and Level 5 (B) scenarios. Percentage represents the percent of the total load needed to reduce mean concentration of all watersheds to 8 mgN/L and 1 mgP/L for Level 2 and 2 mgN/L and 0.02 mgP/L for Level 5. Labels represent Saturated Buffer (BU), Woodchip Bioreactor (BR), Constructed Wetland (W), Nitrogen Rate Reduction (NR), Split Nitrogen Application (NS), Cover Crop (CC), No-Till farming (NT), and the maximum treatment possible when optimizing for the most productive treatment method in each watershed (Max Treatment).

5.2 Optimal Green Infrastructure Deployment Across the US

One of the primary goals of this study was to capture the geospatial intricacies of green nutrient remediation methods. As such, Supplemental Figure 7 illustrates the best green treatment methods to use in each waterbasin when prioritizing maximum nutrient treatment and minimum costs for the Level 2 and Level 5 scenarios. The results between the two scenarios are similar. In both cases, saturated buffers, reduced nitrogen application, and cover crops are used widely for both nitrogen and phosphorus remediation. Con-

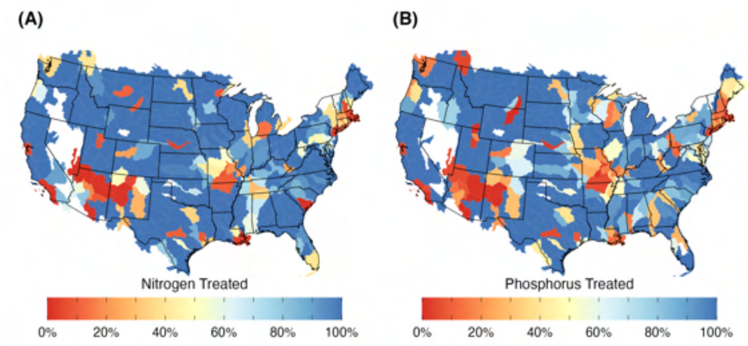


Figure 6: Percent of Nitrogen (A) and Phosphorus (B) treatment possible for green treatment technologies in each waterbasin for the Level 2 scenario of reducing mean nutrient concentrations to 8 mgN/L and 1 mgP/L.

structed wetlands and split nutrient application are used for nitrogen treatment and no-till farming is used widely for phosphorus treatment. In total, 35 of the modeled 63 green treatment combinations are used for either nitrogen or phosphorus in either the Level 2 or Level 5 scenarios.

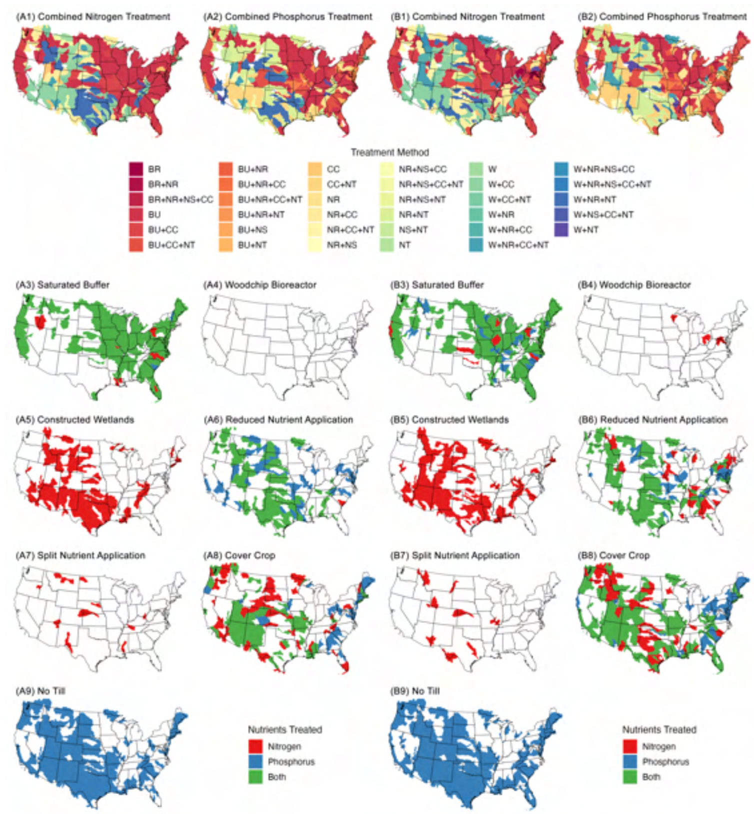


Figure 7: Geographic variability of treatment methods for the optimized green treatment scenario prioritizing minimum cost for the Level 2 scenario (A) and the Level 5 scenario (B). Labels represent Saturated Buffer (BU), Woodchip Bioreactor (BR), Constructed Wetland (W), Nitrogen Rate Reduction (NR), Split Nitrogen Application (NS), Cover Crop (CC), and No-Till farming (NT).

5.3 Global Warming Potential of Gray vs. Green Infrastructure

Similar results shown in the main article for the Level 5 scenario, Supplemental Figure 8 shows GWP of green versus gray technologies across the CONUS for the Level 2 scenario. In this scenario, gray treatment technologies emit 11.9 MtCO2e while green treatment technologies sequester 3.4 MtCO2e annually for the Level 2 scenario which esults in a annual carbon credit potential of 15.3 MtCO2e.

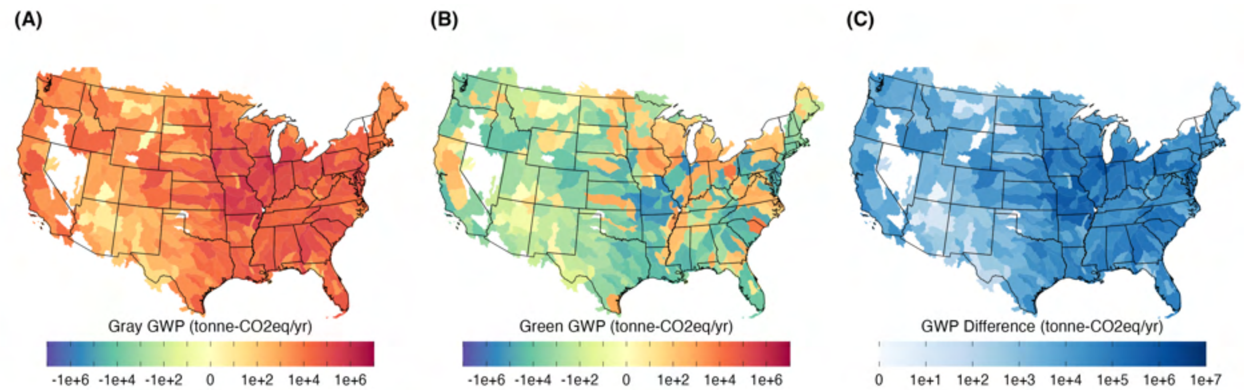


Figure 8: Continental United States global warming potential (GWP) in tonnes of CO2 equivalent emissions per year for removal of nitrogen (to 8 mg/L) and phosphorus (to 1 mg/L) using (A) gray treatment technologies (11.9 MtCO2e/year) and (B) green treatment technologies (-3.4 MtCO2e/year), and (C) net GWP representing potential carbon credit generation (15.3 MtCO2e/year).

5.4 Carbon Financing Potential Green Infrastructure

Similar results shown in the main article for the Level 5 scenario, Supplemental Figure 9 shows costs of green versus gray technologies across the CONUS for the Level 2 scenario. Nutrient treatment costs for the Level 2 scenario were \$14.9B/year and \$10.0B/year for gray and green technologies, respectively. Additionally, the carbon financing potential is \$307 M/yr assuming a carbon credit price of \$20/tonne-CO2eq and the total savings of green treatment technologies when compared to gray treatment and including carbon financing potential is \$5.2B/year. Of the 316 waterbasins in the CONUS which required nutrient treatment, 168 (53%) had green treatment costs cheaper than those of the gray treatment technologies excluding carbon financing revenues. If carbon financing revenue is added, 174 (55%) of waterbasins had green treatment costs cheaper than gray treatment technologies. However, when evaluated as a percent of total nutrients treated in the CONUS, 80.9% of nitrogen and 66.2% of phosphorus is treated in waterbasins where green treatment costs are cheaper than gray treatment technologies when carbon financing revenues are excluded. These values increase to 85.6% of nitrogen and 95.4% of phosphorus treated in the CONUS in waterbasins which green technologies are cheaper when carbon financing revenues are included. Similar to the Level 5 scenario, green treatment costs were significantly impacted by the farmer incentive payments. On a national level, farmer incentive payments make up 49% ($4.9B/year) of the total green treatment costs.

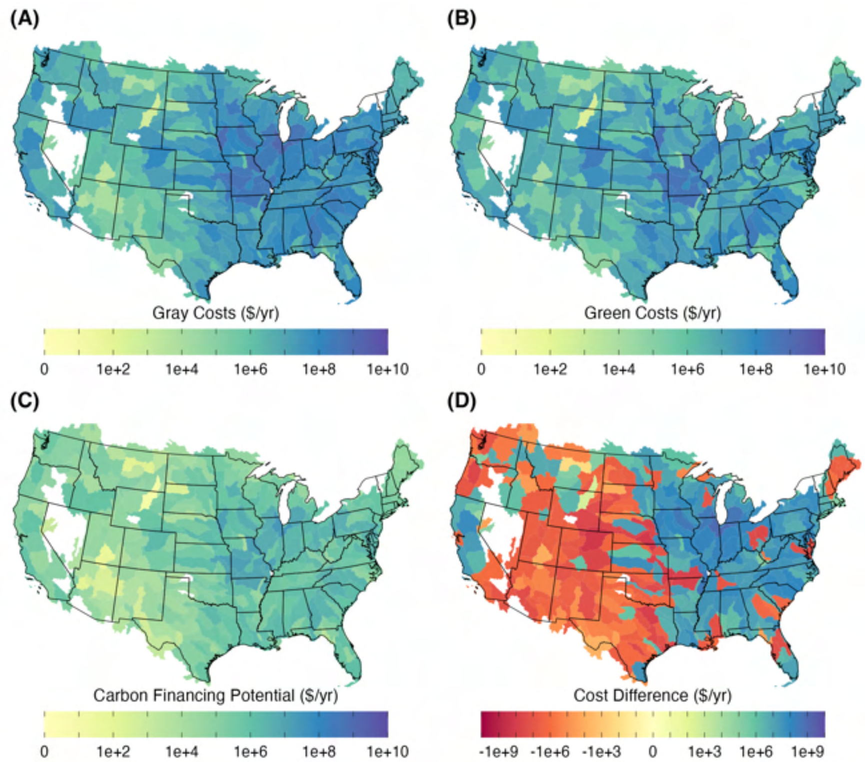


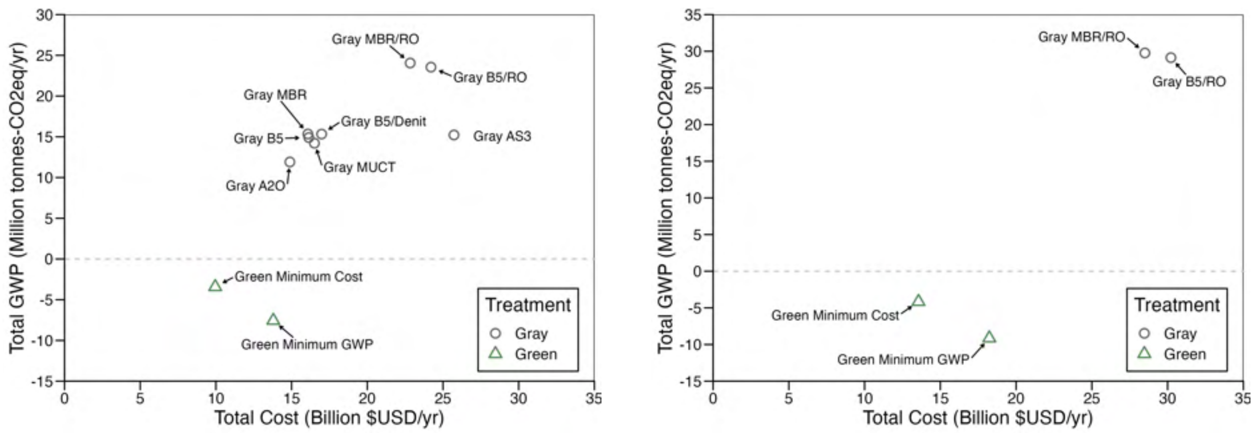
Figure 9: Continental United States water treatment costs for removal of nitrogen (to 8 mg/L) and phosphorus (to 1 mg/L) using (A) gray treatment technologies ($14.9B/year) and (B) green treatment technologies ($10.0B/year), (C) Potential carbon finance revenue ($307 M/year at $20/credit), and (D) net cost difference between gray and green treatment technologies when including carbon financing revenue ($5.2B/year). Negative cost differences show waterbasins where green technologies are more expensive than gray technologies. White space designates waterbasins which didn't have wastewater treatment facilities or didn't require nutrient treatment.

5.5 Cost and Emissions Comparison Between All Green and Gray Technologies

The primary goal of this work to was to evaluate the costs and GWP of nutrient remediation by building additional traditional wastewater treatment facilities (gray infrastructure) compared to green infrastructure. Supplemental Figure 10 shows the costs and GWP required to treat the maximum amount of nitrogen and phosphorus treatment possible with green treatment technologies and all gray treatment technologies considered for the Level 2 and Level 5 treatment scenarios.

Results show that green treatment technologies have the potential to have both less costs and less GWP than gray infrastructure in both scenarios. This result correlates with existing literature on the subject [6, 7, 8]. In the Level 2 scenario, the minimum cost green treatment method has total costs of $10.0 billion/yr and total GWP of -3.4 MtCO2/yr and the minimum emissions green treatment method has total costs of $13.8 billion/yr and total GWP of -7.6 MtCO2/yr. In order to make the minimum emissions scenario financially competitive with the minimum cost scenario, a carbon price of $927 would be required. Comparatively, the cheapest and least environmentally damaging gray treatment method was Anaerobic/Anoxic/Oxic with total costs of $14.9 billion/yr and total GWP of 11.9 MtCO2/yr.

In the Level 5 scenario, the minimum cost green treatment method has total costs of $13.6 billion/yr and total GWP of -4.2 MtCO2/yr and the minimum emissions green treatment method has total costs of $18.2 billion/yr and total GWP of -9.1 MtCO2/yr. In order to make the minimum emissions scenario financially competitive with the minimum cost scenario, a carbon price of $939 would be required. Comparatively, the cheapest gray treatment method was 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Treatment with total costs of $28.4 billion/yr and total GWP of 29.8 MtCO2/yr. The least environmentally damaging gray treatment method was 5-Stage Bardenpho with Sidestream Reverse Osmosis Treatment with total costs of $30.2 billion/yr and total GWP of 29.1 MtCO2/yr.



(a) Level 2 Treatment

(b) Level 5 Treatment

Figure 10: Total Cost and Global Warming Potential (GWP) of the optimum Green treatment methods and each Gray treatment method to meet desired nutrient concentration limits for the Level 2 scenario (a - 8 mgN/L and 1 mgP/L) and Level 5 scenario (b - 2 mgN/L and 0.02 mgP/L). Gray treatment methods include Anaerobic/Anoxic/Oxic (A2O), Activated 3-Sludge System (AS3), 5-Stage Bardenpho (B5), Modified University of Cape Town Process (MUCT), Denitrification Filter (Denit), 4-Stage Bardenpho Membrane Bioreactor (MBR), and Reverse Osmosis Treatment (RO).

5.6 Methods Framework

The following visualizations provide additional information about the methods used to complete this study. Supplemental Figure 11 provides a diagram of the analysis process. Supplemental Table 4 outlines which green technologies require what base technologies in order to be used within the waterbasin. Supplemental Figure 12 provides maps of the required technologies for the green treatment methods shown in Supplemental Table 4.

Table 4: Land limitations placed on green treatment technologies.

Name	*Abbr.*	*Type*	*Tile Drain*	*Buffer*	*Wetlands*	*Fertilizer*	*Current Land Use (%)*	*Farmer Incentive Scaling*
Buffers	BU	Barrier	Yes	Yes	No	No	0.01%	1/15
Bioreactors	BR	Barrier	Yes	No	No	No	0.01%	1/10
Wetland	W	Barrier	No	No	Yes	No	0.4%	1/40
N Rate Reduction	NR	Land	No	No	No	Yes	18.6%	1
Split N Application	NS	Land	No	No	No	Yes	18.6%	1
Cover Crop	CC	Land	No	No	No	No	Varies	1
No-till	NT	Land	No	No	No	No	Varies	1

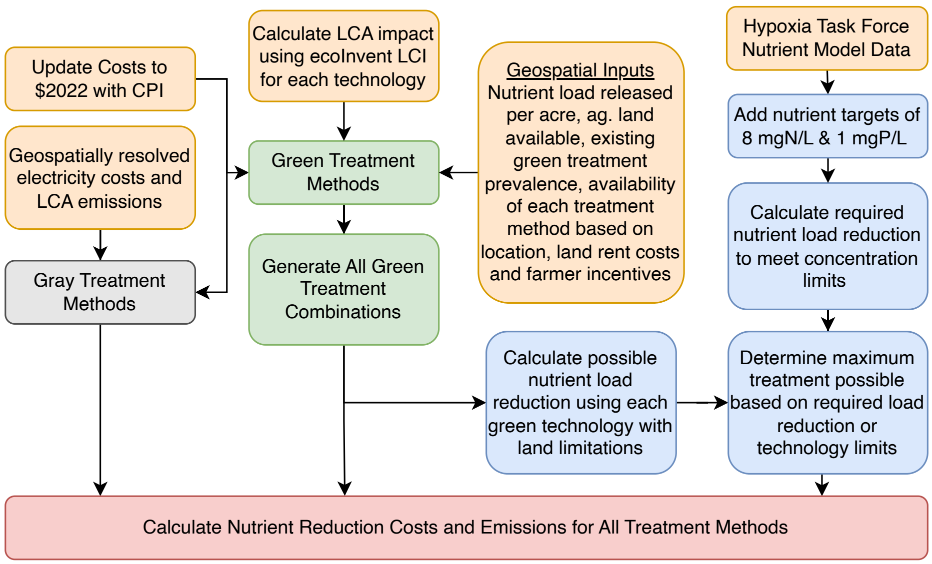


Figure 11: Diagram of the methods used for this study.

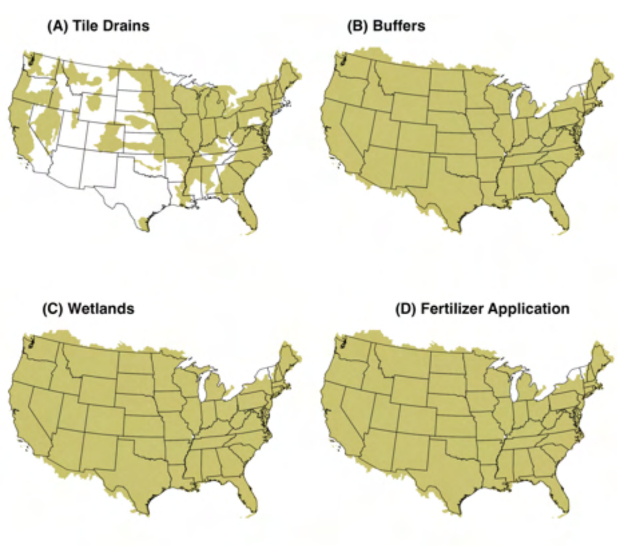


Figure 12: Green water treatment availability by waterbasin for technologies needing tile drainage (A), riparian buffers (B), wetlands (C), and supplemental fertilizer application (D). Data for waterbasin characteristics provided by the US EPA's EnviroAtlas [24].

5.7 Life Cycle Emissions of Green Treatment Methods

Because of limited literature on life cycle emissions of green nutrient treatment scenarios, the GWP of each was estimated using life-cycle inventory data from the EcoInvent 3.71 database, using cut-off analysis, accessed through the software openLCA 1.10.3 (https://openlca.org), and calculated using the Traci 2.1 impact assessment methodology [49, 50]. The GWP estimate for constructed wetlands includes direct land use change effects which were calculated using IPCC methodology [51]. Detailed assumptions for each of the treatment methods are presented in the following sections. The descriptions in the following sections are meant to be used in unison with the supplemental spreadsheet with LCA calculations. For all LCA estimates, calculations were performed for a 50 acre square farm with mean annual nutrient loss of 9.5 kg N/acre and 0.65 kg P/acre [37, 63]. Costs and emissions for green nutrient treatment technologies were assumed to scale linearly based on the number of acres treated, so the 50 acre farm was used to calculate per acre treatment emissions of all treated farmland. Additionally, all green treatment methods that needed a water control device were assumed to use one that was 9 feet tall, 1 foot wide, and 1 foot deep [64] per 50 acres treated.

5.7.1 Saturated Buffer

A saturated buffer is an alternative method to drain the excess water from a farm that uses tile drainage systems. Instead of releasing the runoff directly to a stream, the runoff is released through a riparian buffer using perforated tubing running parallel to the stream. This allows the soil to trap some of the excess nutrients in the runoff before reaching the waterway. Therefore, the environmental impact associated with saturated buffers included the perforated drainage pipe, the water control device, and the excavator needed to install the system. Buffers were assumed to have a 15 year life [65].

5.7.2 Woodchip Bioreactor

A woodchip bioreactor is a large filtration system that uses woodchips to denitrify agricultural runoff. Assumptions used for the LCA of a woodchip bioreactor were gathered from Christianson et al. [37]. It was assumed that a 10 yard long, 5 yard wide, and 3 yard deep bioreactor would be required to treat 50 acres of farmland. This results in 150 cubic yards of woodchips and 165 cubic yards of excavation needed for both the bioreactor and the water control device. Additionally, it was assumed that 6 mil thick plastic would line the bioreactor and it would be covered on top with landscaping fabric. Life cycle emissions were included for all of these components and a 10 year lifetime was assumed.

5.7.3 Constructed Wetland

A constructed wetland consists of building a wetland on part of the farm and running the agricultural runoff through the wetland to trap some of the nutrients. For this, part of farm needs to be converted to a wetland. It was assumed that the wetland size requirement was 2% of treated land plus 2X the wetland size for a buffer [33]. Therefore 6% of the treated land was required for wetland construction. Emissions were included for the wetland's excavation, straw required to help establish the buffer, and seed to start wetland growth. Additionally, direct land use change emissions were also included for constructed wetlands and calculations were performed using IPCC methodology [51]. For these calculations, it was assumed that the farm resided in a cold temperate and dry location and that high activity clay soil existed at the farm location. It was assumed that all above ground biomass was removed and burned prior to creating the wetland. A 40 year wetland life was assumed.

5.7.4 Nutrient Rate Reduction

Nutrient rate reduction consists of farmers applying the proper amount of fertilizer to their field, instead of over fertilizing which eventually leads to extra nutrients running off farms and into streams. A 26.3% percent fertilizer reduction was assumed based on information provided by the University of Nebraska Board of Regents [66]. Reduced fertilizer use results in a net emissions savings compared to traditional nutrient applications because less fertilizer is required.

5.7.5 Split Nutrient Application

Split nutrient application consists of farmers applying part of their fertilizer in the fall and part in the spring. This results in more fertilizer being absorbed by the plants and soils which results in less nutrient runoff. Therefore, the only emissions associated with treatment method were assumed to be that a second fertilizer application.

5.7.6 Cover Crop

Cover cropping is a method to plant a crop of fallow soil to prevent excess nutrient runoff. In this case, it was assumed that ryegrass would be used as the cover crop and emissions associated with ryegrass production were calculated using the EcoInvent inventory and an assumed yield of 700 lbs of ryegrass per acre [67].

5.7.7 No-Till Farming

Conventional tilled farming involves turning over the first 6 - 12 inches of soil before crops are planted. This makes the soil easier to work with, but also removes plant matter from the soil surface and increases erosion risk. Conversely, no-till farming involves not tilling the soil before planting. Therefore, the emissions associated with no-till farming were assumed to be the avoided emissions from not tilling the farmland. Due to the various methods for no-till farming, emissions associated with other no-till practices such as additional weed killer application were not included.

6 Acknowledgements

We acknowledge funding for this study from the Gordon and Betty Moore Foundation (PI Thomas: Mitigating Wildfire and Land-Use Impacts on Watersheds through Carbon Finance Supported Nature-Based Solutions) and the United States Department of Energy (PI Quinn: Agent-based Modeling for the Multi-objective Optimization of Energy Production Pathways [DE-EE0008935]). We also thank the members of the Quinn Lab Group and Mortenson Center in Global Engineering for their insights, Kelli Morrill for her support and feedback, Owen Limb for reminding us to stay curious, and Rori Limb for reminding us of the importance of play.

References

[1] F. Y. Cheng, K. J. Van Meter, D. K. Byrnes, and N. B. Basu. Maximizing US nitrate removal through wetland protection and restoration. *Nature*, 588(7839), 2020. ISSN 14764687. doi: 10.1038/s41586-020-03042-5.

[2] Robert J. Díaz and Rutger Rosenberg. Introduction to environmental and economic consequences of hypoxia. *International Journal of Water Resources Development*, 27(1), 2011. ISSN 07900627. doi: 10.1080/07900627.2010.531379.

[3] EPA. Energy Efficiency for Water Utilities, 2016.

[4] USEPA. Water Quality Trading Policy. Technical report, USEPA, 2003. URL `https://www.epa.gov/system/files/documents/2022-12/Water-Quality-Trading-Policy.pdf`.

[5] D Ross. Updating the Environmental Protection Agency's Water Quality Trading Policy to Promote Market-Based Mechanisms for Improving Water Quality. Technical report, USEPA, 2019. URL `https://www.epa.gov/sites/default/files/2020-10/documents/trading-policy-memo-2019.pdf`.

[6] Yaoze Liu, Bernard A. Engel, Paris D. Collingsworth, and Bryan C. Pijanowski. Optimal implementation of green infrastructure practices to minimize influences of land use change and climate change on hydrology and water quality: Case study in Spy Run Creek watershed, Indiana. *Science of the Total Environment*, 601-602, 2017. ISSN 18791026. doi: 10.1016/j.scitotenv.2017.06.015.

[7] Martin Jaffe. Environmental Reviews & Case Studies: Reflections on Green Infrastructure Economics. *Environmental Practice*, 12(4), 2010. ISSN 1466-0466. doi: 10.1017/s1466046610000475.

[8] Ranish Shakya and Laurent Ahiablame. A synthesis of social and economic benefits linked to green infrastructure, 2021. ISSN 20734441.

[9] Emily Bedell, Olivia Harmon, Katie Fankhauser, Zack Shivers, and Evan Thomas. A continuous, in-situ, near-time fluorescence sensor coupled with a machine learning model for detection of fecal contamination risk in drinking water: Design, characterization and field validation. *Water Research*, 220, 2022. ISSN 18792448. doi: 10.1016/j.watres.2022.118644.

[10] Christopher J. Brown, Stacy D. Jupiter, Simon Albert, Carissa J. Klein, Sangeeta Mangubhai, Joseph M. Maina, Peter Mumby, Jon Olley, Ben Stewart-Koster, Vivitskaia Tulloch, and Amelia Wenger. Tracing the influence of land-use change on water quality and coral reefs using a Bayesian model. *Scientific Reports*, 7(1), 2017. ISSN 20452322. doi: 10.1038/s41598-017-05031-7.

[11] Dylan S. Ahearn, Richard W. Sheibley, Randy A. Dahlgren, Michael Anderson, Joshua Johnson, and Kenneth W. Tate. Land use and land cover influence on water quality in the last free-flowing river draining the western Sierra Nevada, California. *Journal of Hydrology*, 313(3-4), 2005. ISSN 00221694. doi: 10.1016/j.jhydrol.2005.02.038.

[12] Amanda K. Hohner, Charles C. Rhoades, Paul Wilkerson, and Fernando L. Rosario-Ortiz. Wildfires Alter Forest Watersheds and Threaten Drinking Water Quality. *Accounts of Chemical Research*, 52(5), 2019. ISSN 15204898. doi: 10.1021/acs.accounts.8b00670.

[13] Marta Basso, Diana C.S. Vieira, Tiago B. Ramos, and Marcos Mateus. Assessing the adequacy of SWAT model to simulate postfire effects on the watershed hydrological regime and water quality. *Land Degradation and Development*, 31(5), 2020. ISSN 1099145X. doi: 10.1002/ldr.3476.

[14] Danielle Loiselle, Xinzhong Du, Daniel S. Alessi, Kevin D. Bladon, and Monireh Faramarzi. Projecting impacts of wildfire and climate change on streamflow, sediment, and organic carbon yields in a forested watershed. *Journal of Hydrology*, 590, 2020. ISSN 00221694. doi: 10.1016/j.jhydrol.2020.125403.

[15] Sarah Cashman, Sam Arden, Ben Morelli, Jessica Gray, Deborah Bartram, and Debra Falatko. Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants. Technical report, EPA, Eastern Research Group, August 2021. URL https://www.epa.gov/system/files/documents/2023-06/life-cycle-nutrient-removal.pdf. https://www.epa.gov/system/files/documents/2021-08/life-cycle-nutrient-removal.pdf.

[16] USEPA. Nutrient Reduction Progress Tracker. 2018. URL https://www.acwa-us.org/wp-content/uploads/2018/03/Nutrient-Reduction-Progress-Tracker-Version-1.0-2017-Report.pdf.

[17] Michael W. Falk, David J. Reardon, J.B. Neethling, David L. Clark, and Amit Pramanik. Striking the Balance between Nutrient Removal, Greenhouse Gas Emissions, Receiving Water Quality, and Costs. *Water Environment Research*, 85(12):2307–2316, 2013. ISSN 1061-4303. URL https://www.jstor.org/stable/24584943. Publisher: Water Environment Federation.

[18] Evan Thomas, Jean Ntazinda, and Styvers Kathuni. Applying climate reparative finance toward water security. *Science of The Total Environment*, 875:162506, June 2023. ISSN 0048-9697. doi: 10.1016/j.scitotenv.2023.162506. URL https://www.sciencedirect.com/science/article/pii/S0048969723011221.

[19] Pedro Piris-Cabezas, Ruben N. Lubowski, and Gabriela Leslie. Estimating the potential of international carbon markets to increase global climate ambition. *World Development*, 167:106257, July 2023. ISSN 0305-750X. doi: 10.1016/j.worlddev.2023.106257. URL https://www.sciencedirect.com/science/article/pii/S0305750X2300075X.

[20] Ernst and Young. Essential, expensive and evolving: The outlook for carbon credits and offsets An EY Net Zero Centre report. Technical report, 2022. URL https://assets.ey.com/content/dam/ey-sites/ey-com/en_au/topics/sustainability/ey-net-zero-centre-carbon-offset-publication-20220530.pdf.

[21] Ben Groom and Frank Venmans. The social value of offsets. *Nature*, pages 1–6, July 2023. ISSN 1476-4687. doi: 10.1038/s41586-023-06153-x. URL https://www.nature.com/articles/s41586-023-06153-x. Publisher: Nature Publishing Group.

[22] United States Geological Survey. Hydrologic Unit Codes (HUCs) Explained, 2023. URL https://nas.er.usgs.gov/hucs.aspx.

[23] United States Geological Survey. Watershed Boundary Dataset (WBD), September 2022. URL https://datagateway.nrcs.usda.gov/catalog/productdescription/wbd.html.

[24] US EPA. EnviroAtlas Data Download, September 2015. URL https://www.epa.gov/enviroatlas/forms/enviroatlas-data-download.

[25] US EPA. Nutrient Model (Hypoxia Task Force Search), 2022. URL https://echo.epa.gov/help/loading-tool/hypoxia-task-force-search-help/about-the-nutrient-model.

[26] US EPA. Water Pollutant Loading Tool - Data Downloads | ECHO | US EPA, 2023. URL https://echo.epa.gov/trends/loading-tool/get-data.

[27] Michael W. Falk, David J. Reardon, J.B. Neethling, David L. Clark, and Amit Pramanik. Striking the Balance between Nutrient Removal, Greenhouse Gas Emissions, Receiving Water Quality, and Costs. *Water Environment Research*, 85(12), 2013. ISSN 10614303. doi: 10.2175/106143013x13807328848379.

[28] U.S. Energy Information Administration (EIA). Annual Energy Outlook 2021, February 2021. URL https://www.eia.gov/outlooks/aeo/.

[29] US EPA. Emissions & Generation Resource Integrated Database (eGRID), July 2020. URL https://origin-awswest-www.epa.gov/egrid.

[30] Joris Van den Bossche, Kelsey Jordahl, Martin Fleischmann, James McBride, Jacob Wasserman, Matt Richards, Adrian Garcia Badaracco, Alan D. Snow, Jeff Tratner, Jeffrey Gerard, Brendan Ward, Matthew Perry, Carson Farmer, Geir Arne Hjelle, Mike Taves, Ewout ter Hoeven, Micah Cochran, rraymondgh, Sean Gillies, Giacomo Caria, Lucas Culbertson, Matt Bartos, Nick Eubank, Ray Bell, sangarshanan, John Flavin, Sergio Rey, maxalbert, Aleksey Bilogur, and Christopher Ren. geopandas/geopandas: v0.13.2, June 2023. URL https://doi.org/10.5281/zenodo.8009629.

[31] US Bureau of Labor Statistics. Consumer Price Index (CPI), 2023. URL https://www.bls.gov/cpi/.

[32] US Bureau of Labor Statistics. Bureau of Labor Statistics Data, 2023. URL https://data.bls.gov/pdq/SurveyOutputServlet.

[33] Laura Christianson, Jane Frankenberger, Chris Hay, Matt Helmers, and Gary Sands. Ten Ways to Reduce Nitrogen Loads from Drained Cropland in the Midwest., 2016. URL http://draindrop.cropsci.illinois.edu/wp-content/uploads/2016/09/Ten-Ways-to-Reduce-Nitrate-Loads_IL-Extension-_2016.pdf. http://draindrop.cropsci.illinois.edu/wp-content/uploads/2016/09/ten-ways-factsheet-summary-FINAL.pdf.

[34] Illinois Water Resources Center. Nutrient loss reduction: Using science to find the right practices for your field. Technical report, 2016. URL http://draindrop.cropsci.illinois.edu/wp-content/uploads/2016/10/IL-NLRS-Practice-Factsheet_2016.pdf.

[35] Laura Christianson, John Tyndall, and Matthew Helmers. Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage. *Water Resources and Economics*, 2-3:30–56, October 2013. ISSN 2212-4284. doi: 10.1016/j.wre.2013.09.001. URL https://www.sciencedirect.com/science/article/pii/S2212428413000194.

[36] Laura Christianson. Nitrogen Loss Reduction Practices: What Do They Cost? *farmdoc daily*, 8(210), November 2018. URL https://farmdocdaily.illinois.edu/2018/11/nitrogen-loss-reduction-practices-what-do-they-cost.html.

[37] Laura E. Christianson. Woodchip Bioreactor: A science-based option to reduce nitrate loss, 2018. URL http://draindrop.cropsci.illinois.edu/wp-content/uploads/2019/12/Christianson-et-al_2018_Woodchip-Bioreactor_2pg-Factsheet.pdf.

[38] Baojing Gu, Xiuming Zhang, Shu Kee Lam, Yingliang Yu, Hans J. M. van Grinsven, Shaohui Zhang, Xiaoxi Wang, Benjamin Leon Bodirsky, Sitong Wang, Jiakun Duan, Chenchen Ren, Lex Bouwman, Wim de Vries, Jianming Xu, Mark A. Sutton, and Deli Chen. Cost-effective mitigation of nitrogen pollution from global croplands. *Nature*, 613(7942):77–84, January 2023. ISSN 1476-4687. doi: 10.1038/s41586-022-05481-8. URL https://www.nature.com/articles/s41586-022-05481-8. Number: 7942 Publisher: Nature Publishing Group.

[39] Qi Zhou, Haimeng Sun, Lixia Jia, Weizhong Wu, and Jianlong Wang. Simultaneous biological removal of nitrogen and phosphorus from secondary effluent of wastewater treatment plants by advanced treatment: A review. *Chemosphere*, 296:134054, June 2022. ISSN 0045-6535. doi: 10.1016/j.chemosphere.2022.134054. URL https://www.sciencedirect.com/science/article/pii/S0045653522005471.

[40] D. B. Jaynes and T. M. Isenhart. Performance of Saturated Riparian Buffers in Iowa, USA. *Journal of Environmental Quality*, 48(2):289–296, 2019. ISSN 1537-2537. doi: 10.2134/jeq2018.03.0115. URL https://onlinelibrary.wiley.com/doi/abs/10.2134/jeq2018.03.0115. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.2134/jeq2018.03.0115.

[41] D. B. Jaynes and T. M. Isenhart. Reconnecting Tile Drainage to Riparian Buffer Hydrology for Enhanced Nitrate Removal. *Journal of Environmental Quality*, 43(2):631–638, 2014. ISSN 1537-2537. doi: 10.2134/jeq2013.08.0331. URL https://onlinelibrary.wiley.com/doi/abs/10.2134/jeq2013.08.0331. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.2134/jeq2013.08.0331.

[42] Nathan Utt, Dan Jaynes, and Jessica Albertsen. Demonstrate and Evaluate Saturated Buffers at Field Scale to Reduce Nitrates and Phosphorus from Subsurface Field Drainage Systems. Techni-

cal report, December 2015. URL https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/EPAS/natural-resouces-analysis/pdfs/admc_final_report.pdf.

[43] Iowa Department of Agriculture and Land Stewardship, Iowa Department of Natural Resources, and Iowa State University. *Iowa Nutrient Reduction Strategy 2018-19 Annual Progress Report*. June 2020. URL https://store.extension.iastate.edu/product/Iowa-Nutrient-Reduction-Strategy-2018-19-Annual-Progress-Report.

[44] Julie Harrold. Indiana's State Nutrient Reduction Strategy. Technical report, February 2021.

[45] Arkansas Department of Agriculture Natural Resources Division. 2022 Arkansas Nutrient Reduction Strategy. Technical report, 2022.

[46] Iowa State University. Reducing Nutrient Loss: Science Shows What Works, February 2017. URL https://www.cals.iastate.edu/files/misc/183758/reducing-nutrient-loss-science-shows-what-works.pdf.

[47] Soil and Water Outcomes Fund. Soil and Water Outcomes Fund Produces More Than Tenfold Increase in Environmental Outcomes in 2021, December 2021. URL https://theoutcomesfund.com/news-release-2021-environmental-outcomes.

[48] United States Department of Agriculture. 2022 USDA/NASS QuickStats Land Rent Costs, 2022. URL https://quickstats.nass.usda.gov/results/58B27A06-F574-315B-A854-9BF568F17652#7878272B-A9F3-3BC2-960D-5F03B7DF4826.

[49] Gregor Wernet, Christian Bauer, Bernhard Steubing, Jürgen Reinhard, Emilia Moreno-Ruiz, and Bo Weidema. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 21(9):1218–1230, September 2016. ISSN 1614-7502. doi: 10.1007/s11367-016-1087-8. URL https://doi.org/10.1007/s11367-016-1087-8.

[50] Jane Bare, Daniel Young, S Qam, Matthew Hopton, and S Chief. Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI). *US Environmental Protection Agency: Washington, DC, USA*, 2012.

[51] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006. URL https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

[52] Naomi Nakagaki, Michael Wieczorek, and Sharon L. Qi. Estimates of Subsurface Tile Drainage Extent for the Conterminous United States, early 1990s, 2016. URL https://www.sciencebase.gov/catalog/item/get/56e86a60e4b0f59b85d71ff9.

[53] Zachary Sugg. *Assessing U.S. Farm Drainage*. January 2007. ISBN 978-1-56973-665-4. URL https://www.wri.org/research/assessing-us-farm-drainage.

[54] United States Department of Agriculture. National Agricultural Statistics Service: Quick Stats, 2022. URL https://quickstats.nass.usda.gov/.

[55] United States Department of Agriculture National Agricultural Statistics Service. Iowa Ag News - Farms and Land in Farms. Technical report, February 2021. URL https://www.nass.usda.gov/Statistics_by_State/Iowa/Publications/Other_Surveys/2021/IA-Farms-02-21.pdf.

[56] US EPA. Estimated Total Nitrogen and Total Phosphorus Loads and Yields Generated within States, July 2023. URL https://www.epa.gov/nutrient-policy-data/estimated-total-nitrogen-and-total-phosphorus-loads-and-yields-generated.

[57] Scott W. Ator. Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the northeastern United States. USGS Numbered Series 2019-5118, U.S. Geological Survey, Reston, VA, 2019. URL http://pubs.er.usgs.gov/publication/sir20195118. Code Number: 2019-5118 Code: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the northeastern United States Publication Title: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the northeastern United States Reporter: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the northeastern United States Series: Scientific Investigations Report IP-103253.

[58] Anne B. Hoos and Victor L. Roland II. Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in the southeastern United States. USGS Numbered Series 2019-5135, U.S. Geological Survey, Reston, VA, 2019. URL http://pubs.er.usgs.gov/publication/sir20195135. Code Number: 2019-5135 Code: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in the southeastern United States Publication Title: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in the southeastern United States Reporter: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in the southeastern United States Series: Scientific Investigations Report IP-101532.

[59] Dale M. Robertson and David A. Saad. Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the midwestern United States. USGS Numbered Series

2019-5114, U.S. Geological Survey, Reston, VA, 2019. URL http://pubs.er.usgs.gov/publication/sir20195114. Code Number: 2019-5114 Code: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the midwestern United States Publication Title: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the midwestern United States Reporter: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the midwestern United States Series: Scientific Investigations Report IP-103244.

[60] Daniel R. Wise, David W. Anning, and Olivia L. Miller. Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment transport in streams of the southwestern United States. USGS Numbered Series 2019-5106, U.S. Geological Survey, Reston, VA, 2019. URL http://pubs.er.usgs.gov/publication/sir20195106. Code Number: 2019-5106 Code: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment transport in streams of the southwestern United States Publication Title: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment transport in streams of the southwestern United States Reporter: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment transport in streams of the southwestern United States Series: Scientific Investigations Report IP-105772.

[61] Daniel R. Wise. Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the Pacific region of the United States. USGS Numbered Series 2019-5112, U.S. Geological Survey, Reston, VA, 2019. URL http://pubs.er.usgs.gov/publication/sir20195112. Code Number: 2019-5112 Code: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the Pacific region of the United States Publication Title: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the Pacific region of the United States Reporter: Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the Pacific region of the United States Series: Scientific Investigations Report IP-103780.

[62] Mahdi Fasihi, Olga Efimova, and Christian Breyer. Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, 224:957–980, July 2019. ISSN 0959-6526. doi: 10.1016/j.jclepro.2019.03.086. URL https://www.sciencedirect.com/science/article/pii/S0959652619307772.

[63] Christine Alewell, Bruno Ringeval, Cristiano Ballabio, David A. Robinson, Panos Panagos, and Pasquale Borrelli. Global phosphorus shortage will be aggravated by soil erosion. *Nature Communications*, 11(1):

4546, September 2020. ISSN 2041-1723. doi: 10.1038/s41467-020-18326-7. URL https://www.nature.com/articles/s41467-020-18326-7. Number: 1 Publisher: Nature Publishing Group.

[64] Agri Drain Corporation. Inline Water Level Control Structure. URL https://www.agridrain.com/webres/File/Inline%20Water%20Level%20Control%20Structure(1).pdf.

[65] United States Department of Agriculture. Operation & Maintenance Plan Saturated Buffer (Code 604). URL https://efotg.sc.egov.usda.gov/api/CPSFile/27371/604_VT_OM_Saturated_Buffer_2020.

[66] The Board of Regents of the University of Nebraska. How to properly apply nitrogen fertilizer. URL https://water.unl.edu/documents/Section%20G.pdf.

[67] Rocky Lemus. Annual Ryegrass Performance in Mississippi: Long-Term Yield Production.