Journal of Geoscience and Environment Protection, 2026, 14(8), 186-197
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Southeastern Missouri Phosphorus and Sulfur Soil Concentrations in Mississippi River Floodplain Environments

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How to cite this paper: Aide, M., & Aide, C. (2026). Southeastern Missouri Phosphorus and Sulfur Soil Concentrations in Mississippi River Floodplain Environments. *Journal of Geoscience and Environment Protection, 14,* 186-197.
https://doi.org/10.4236/gep.2026.148010

Received: July 25, 2026
Accepted: August 28, 2026
Published: August 31, 2026

Abstract

Nitrogen and phosphorus fertilizer amendments increase the nutrient content of soils to support plant growth and development. With overland and subsurface water flow, wind and water induced erosion, and other transport pathways, waterways will become impacted by these nutrients. In the Gulf of Mexico, nitrogen and phosphorus contributed to the prevailing hypoxia zone. We investigated two soil locations on the floodplain of the Modern Mississippi River in Missouri. One soil location had two pedons of the Commerce soil series (Endoaquepts) and the other soil location had two pedons of the Caruthersville soil series (Udifluvents). Soil analysis indicates that both soil sites exhibited labile phosphorus exceeding 100% soil phosphorus index values. Aqua regia digestion indicates that appreciable quantities of phosphorus and sulfur exist. Plant tissue analysis confirms that these soils provide ample nutrients for the existing vegetation. We conclude that maintaining forested acreages along the floodplains of the Mississippi River mitigate phosphorus riverine transport to the Gulf of Mexico, reducing the severity of the hypoxia zone.

Keywords

Legacy Phosphorus, Sulfate, Mississippi River Quality, Gulf Mexico Hypoxia, Eutrophication, Forest Soils

1. Introduction

The Mississippi River is the largest river in North America, and its watershed drains 41% of the conterminous United States. Turner (2024) evaluated water quality in the Mississippi River adjacent to the State of Louisiana during the time frame spanning from 1901 to 2019. In 2019, the Mississippi River exported 91%

of the nitrogen and 88% of the phosphorus into the Gulf of Mexico, supporting the largest hypoxia zone in the Western Atlantic (Turner, 2024; Rabalais & Turner, 2019). It was estimated in 2019 that the Mississippi River exported 20.1 Tg total Carbon yr^{-1} and 4.2 Tg organic carbon yr^{-1} (Turner, 2024).

Savenko and Savenko (2022) noted that the global average (median mean) total phosphorus river concentrations for agricultural catchments was 0.25 $mg \cdot L^{-1}$. Mississippi River phosphorus concentrations typically range from 0.10 to 0.50 $mg \cdot L^{-1}$; however, these concentration levels significantly fluctuate depending on the rainfall, runoff, baseflow and location (Mengistu et al., 2023). Major phosphorus contributions to the Mississippi River occur in the Upper Mississippi River Basin and the Missouri River Basin because of crop fertilization and subsurface drainage tiles. In natural, healthy aquatic systems, phosphorus concentrations are typically below 0.03 $mg \cdot L^{-1}$ (Savenko & Savenko 2022; Welch et al., 2010). Sulfate concentrations in the Mississippi River generally range from 28 to 48 $mg \cdot L^{-1}$ (Killingsworth and Bao (2015) showed that Mississippi River sulfate concentrations arise from natural or geologic sources (25% ± 6%) and anthropogenic sources (75% ± 6%). Coal usage is likely the dominant anthropogenic source of modern Mississippi River sulfate; however, electrical generation is shifting from coal combustion to natural gas.

2. Phosphorus and Sulfur Landscape Interactions and Management

2.1. Soil Phosphorus and Sulfur Expression in the Mississippi River Watershed

Soil phosphorus concentrations croplands and forage lands in the Central United States are frequently at 100% fertility index or greater, a feature attributed to fertilization and manure applications. Ringeval et al. (2017) determined phosphorus inherited from natural soils that were subsequently converted to agriculture and the inevitable imposition of farming practices were the main influencers of cropland soil P variability, but the magnitude of their contribution was predicated on the total soil P and labile inorganic P. Ringeval et al. (2024) estimated a global averaged inorganic labile P at 187 $kg \cdot P \cdot ha^{-1}$ for cropland and 91 $kg \cdot P \cdot ha^{-1}$ for grassland, but the values vary based on mineralization rates. In humid regions, Scherer (2009) noted that sulfate is the sulfur source for immediate plant uptake; however, sulfate only contributes up to 5% of total sulfur pool. In most mid-western soils, sulfur covalently bonded in soil organic materials is approximately 95% of total sulfur pool. Sulfur content varies widely, given the presence of gypsum or pyrite and sulfur atmospheric deposition.

Much has been published concerning soil phosphorus (Khasawneh et al., 1980). Recently, Deiss et al. 2018) noted the major influencers of phosphorus bioavailability include: 1) edaphic factors (soil pH, clay contents, Fe oxyhydroxides), 2) Climate (temperature and precipitation), 3) (weathering and parent material), 4) biological cycling (root exudates and phosphatase enzymes mineralize organic P compounds (inositol hexakisphosphates) into bioavailable phosphate). Soil sulfur chemistry has been reviewed by Schoenau and Malhi (2008).

2.2. Phosphorus Transport between Aquifers and the Mississippi River

The Mississippi River receives and provides water to aquifers underlying its floodplains, with aquifer gains during large river discharge events and aquifer declines during baseflow intervals. Welch et al. (2010) demonstrated that dissolved phosphorus concentrations in the Mississippi River valley alluvial aquifer are considered elevated and range from 0.12 to 1.2 mg·L^{-1}. They documented that the dissolved iron concentrations increase with reducing conditions and subsequently facilitate phosphorus transport. More recently, Justus (2022) reported that groundwater in the Mississippi Delta had some of the highest phosphorus concentrations and widespread reducing conditions in shallow groundwater and long-term P fertilization are important parameters.

Analyzing Mississippi River water and its associated sediments, Zhang et al. (2012) observed that during significant flooding events soluble reactive P, dissolved organic P, Fe, and Mn concentrations increased because of decreased sediment redox potential. Botero-Acosta et al. (2025) noted that watersheds dominated by urban and cultivated cropland frequently had elevated phosphorus concentrations.

2.3. Legacy Phosphorus and Mississippi River Phosphorus Concentrations

Phosphorus legacy is a soil condition that occurs when soils have had a history of phosphorus fertilization that intensifies the phosphorus bioavailability and predisposes phosphorus overland and subsurface flow to freshwater resources. In the Lower Mississippi Alluvial Plain, Witthaus et al. (2025) documented that phosphorus legacy provided moderate levels of available P and that soil phosphorus concentrations are higher than expected when considering currently reduced phosphorus fertilizer application rates. The data supports the premise that naturally high levels of soil phosphorus exist across the region's soils.

Water quality degradation, because of legacy soil phosphorus export, frequently results in water resource eutrophication. Dari et al. (2018) proposed to utilize the molar ratio of extractable P/(Al + Fe), called the soil phosphorus saturation ratio, to estimate whether soils in humid climates may act as either phosphorus sinks or sources. The soil phosphorus saturation ratio was an effective threshold value, above which water-soluble phosphorus abruptly increases. The threshold phosphorus saturation ratio of 0.10 appears appropriate for acidic, humid-region soils. Dari et al. (2018) further proposed that the soil phosphorus saturation ratio in acid soils has the potential of estimating legacy P. Using studies conducted in Europe and the southeastern United States, Nair (2014) determined that when soils are below a threshold phosphorus saturation ratio value, the equilibrium phosphorus concentration is low, and any subsequent phosphorus export would be of low to moderate intensity.

2.4. Soil and Land Management Practices Mitigating Soil Phosphorus Transfer to Water Resources

With the status of freshwater and marine eutrophication, phosphorus transport mitigation to water resources is an area of intense research (Rabalais & Turner, 2019). Land management and soil engineering are leading stewardship activities to limit nutrient migration from agricultural fields to freshwater resources. Byrnes et al. (2026) listed and discussed important farming practices that address soil management of legacy phosphorus, and the land management practices include 1) modern nutrient stewardship to reduce nutrient runoff, 2) appropriate manure application rates, and 3) development and implementation of a well-designed phosphorus targeted drawdown program. In accessing legacy phosphorus, Doydora et al. (2020) proposed using cover crops, organic acid amendments, or phosphorus-solubilizing microbes to convert inert phosphorus into bioavailable phosphorus.

Solangi et al. (2023) proposed agricultural management techniques to reduce the incidence of soil legacy phosphorus, including liming acid soils, appropriate crop rotations, intercropping, cover crops, modern soil fertility programming, efficient crop varieties, and inoculation with P-solubilizing microorganisms. In Canada, Coppolino et al. (2022) determined that riparian wetlands can potentially intercept phosphorus mobilized from upland soils before it reaches connecting waterways. Vilmin et al. (2022) documented that appropriately designed reservoirs support phosphorus retention of P. In the Mississippi Alluvial Valley, Baker et al. (2018) noted that conservation practices such as conservation tillage, cover crops, and variable-rate fertilization are essential for mitigating agricultural runoff. However, runoff concentrations are more heavily influenced by extreme precipitation events than conservation activities. Osmond et al. (2019) addressed water quality degradation attributed to erosion, runoff, or leaching. They proposed that land management practices must be implemented as a system of practices which increase redundancy and consider multiple phosphorus transport pathways. Implementation planning must initially consider the entire watershed to guarantee land practices are appropriately placed in critical source areas.

2.5. Manuscript Objectives

The objectives of this study are: 1) to briefly review phosphorus and sulfur soil fertility in the Mississippi River Basin, with an emphasis on phosphorus as a potential eutrophication species, and 2) to document the sulfur and phosphorus accumulation in several annually inundated floodplain soils of the Mississippi River in southeastern Missouri.

3. Materials and Methods

3.1. Study Area

The study area is in east-central Missouri (Cape Girardeau County and Scott

County) and residing in annual floodplain regions of the Mississippi River. The dominant forest classification is a temperate mesic forest, frequently a habitat having moderate, well-balanced moisture levels, deep and nutrient-rich soils, with a closed canopy of deciduous or mixed trees. Common forest species within the Mississippi River floodplain include eastern cottonwood (*Populus deltoides*), white oak (*Quercus alba*), yellow poplar (*Liriodendron tulipifera*), American sycamore (*Platanus occidentalis*), green ash (*Fraxinus pennsylvanica*), sweetgum (*Liquidambar styraciflua*), and bald cypress (*Taxodium distichum*) and others. The climate is humid continental, and the annual rainfall is 1.07 m and average daily annual air temperature is 14˚C (Festervand, 1981). Annual flooding durations are generally 1 to 7 days; however, long flood intervals may occur. The modern Mississippi River floodplain soils are Holocene age and include the soil orders Entisols, Inceptisols, Mollisols, and Vertisols.

Two pedons of the Commerce series (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) and two pedons of the Caruthersville series (Coarse-silty, mixed, superactive, calcareous, thermic Typic Udifluvents) were morphologically described and sampled. The vegetation at the Caruthersville site consisted of Giant River Cane (*Arundinaria gigantea*). The Commerce pedons presented A-Bw-Bg-Bssg horizon sequences and displayed ochric and cambic horizons, whereas the Caruthersville pedons presented A-C-Cg horizon sequences and displayed ochric epipedons. The Commerce site vegetation consisted of multiple tree species typical of a temperate mesic forest.

The Commerce pedons were located at Universal Transverse Mercator latitude, 277755, 4133200, 16S, whereas the Caruthersville pedons were located at Universal Transverse Mercator latitude, 283178, 4115480, 16S. At each site, soil samples were collected at 15, 30, 46, 61, 91 cm depths, with the Caruthersville also sampled at 122 cm. At each site, the pedon spacing was approximately 15 meters.

3.2. Laboratory Protocols

Soil pH in water, exchangeable cations, total neutralizable acidity, soil organic matter content by loss on ignition, Bray-1 phosphorus, and 2*M* potassium chloride extractable SO_4-S were determined by the University Missouri-Columbia Soil Testing Laboratory. For slightly alkaline soils, the Bray-1 phosphorus test may not fully characterize the phosphorus content as representing plant-available phosphorus. In Missouri, an experimentally defined empirical formula based on the actual soil test value and the Bray-1 P desired value (22.5 $mg \cdot P \cdot kg^{-1}$) estimates the intensity of surplus or deficient phosphorus for row-crop and forage fertilizer recommendations. If the actual soil test and desired soil test values are equal, the soil is said to be at 100% soil test level or 100% soil phosphorus index. The Bray-1 phosphorus soil test levels vary with crop selection, with the typical ideal soil test value for row-crops established as 22.5 $mg \cdot P \cdot kg^{-1}$. Typical SO_4-S soil test values are: 1) very low (0 - 4 $mg \cdot kg^{-1}$), 2) low (4 - 7 $mg \cdot kg^{-1}$), 3) medium (8 - 11 $mg \cdot kg^{-1}$), 4) high (12 - 15 $mg \cdot kg^{-1}$), and 5) very high (16+ $mg \cdot kg^{-1}$) (Kaiser & Eliasou, 2018).

An aqua-regia digestion was performed to estimate near-total elemental concentrations. In this procedure, 0.25 g of finely ground fine earth fraction was digested in 0.01 liter of aqua regia (1 HCl:3HNO_3) for one hour, followed by 0.45 µm filtering with an aliquot analyzed using inductively coupled plasma - atomic emission spectrometry. Quality assurance and analytical accuracy involved four certified reference materials and duplicate samples. Soil analysis for the aqua regia digestion was performed by Activation Laboratories (Ancaster, Ontario).

3.3. Plant Tissue Analysis

Vegetation from the soil selection areas was performed. Plant sampling was performed mid-summer (July 2026) with selection of fully expanded, mature leaves. Mulberry (*Morus spp*.) was selected for the Commerce soil site and Giant River Cane (*Arundinaria gigantea*) was selected for the Caruthersville soil site. Plant material was analyzed for N, P, K, Mg, Ca, S, Na, Fe, Mn, B, Cu, and Zn by Midwest Laboratories (Omaha NE).

Standard macronutrient sufficiency range concentrations (% of total dry leaf weight) for selected trees are nitrogen (2.0% - 3.0%), phosphorus (0.1% - 0.3%), potassium (1.0% - 2.5%), calcium (1.0% - 3.0%), magnesium (0.3% - 0.5%) and sulfur (0.2% - 0.5%) (Penn State College of Agricultural Sciences, verified July 2026). These ranges should be regarded as general guidelines, as specific trees do differ.

4. Results and Discussion

4.1. Soil Characterization

The dominant soil physical (soil texture and horizon characterization) and chemical properties (pH, soil organic matter, cation exchange capacity) of each soil profile are consistent with the soil's taxonomy. The Caruthersville pedons exhibit silt loam to sandy loam horizons, slightly alkaline pH levels and limited soil organic matter contents (**Table 1**). The soil organic matter content is 1.1% in the A horizons, whereas the soil organic matter contents in the deeper horizons irregularly alternate from 0.4 to 1.3%. The Bray-1 phosphorus concentrations are appreciably greater than the 22.5 ppm threshold for a 100% soil fertility index. Calcium is the dominant exchangeable cation, with the exchange capacity varying from 10.0 to 23.3 $cmol \cdot kg^{-1}$. The exchange capacity values roughly correspond with the clay content. The unit $cmol \cdot kg^{-1}$ is a centimole of protonic charge per kilogram.

The Commerce pedons exhibit silty clay to clay-textured horizons, having slightly alkaline pH levels and moderate soil organic matter contents (**Table 2**). The soil organic matter content is 3.4% in A horizon, with deeper horizons having somewhat smaller values, ranging from 2.2% to 3.1%. The Bray-1 phosphorus concentrations are substantially greater than the 22.5 ppm threshold for a 100% soil fertility index. Calcium is the dominant exchangeable cation, with the exchange capacity varying from 23.6 to 40.4 $cmol \cdot kg^{-1}$.

Table 1. Routine chemical composition of the Caruthersville soil pedons.

Horizon	Depth	pH	SOM	SO_4-S	P	CEC
	cm	water	%	ppm	ppm	cmol/kg
A	15	7.7	1.1	34.3	50	16.9
C1	30	7.9	0.6	51.7	51	19.8
C2	46	8	0.6	45.8	59	17.8
C3	61	7.9	1.6	57.3	23	23.3
C4	91	8	0.8	10.7	39	14.4
C5	122	8.1	1	6	34	16.5
A	15	8.1	1.1	6.1	45	16.6
C1	30	8.1	0.8	4.3	52	15.5
C2	46	8.1	0.6	2.3	59	14
C3	61	8.1	0.6	3.4	61	13.5
C4	91	7.9	1.3	7.3	62	14.2
C5	122	8.1	0.4	2.6	64	10

Table 2. Routine chemical composition of the Commerce soil pedons.

Horizon	Depth	pH	SOM	SO_4-S	P	CEC
	cm	water	%	ppm	ppm	meg/100g
A	15	7.8	3.4	6.1	37	34.8
Bw1	30	7.8	2.6	3.6	46	26.3
Bw2	46	7.9	2.3	3.1	38	27.5
Bw3	61	7.9	2.5	2.2	44	23.6
Bw4	91	7.6	2.9	2.1	48	29
A	15	7.9	3.4	4.9	33	24.2
Bw1	30	7.9	3.1	3.2	44	28
Bw2	46	7.9	2.3	2.3	33	38.6
Bw3	61	7.8	2.2	2.6	37	40.4
Bw4	91	7.7	2.2	2.7	43	29.4

The aqua regia digestion phosphorus and sulfur concentrations (**Table 3**) are appreciably greater than the Bray-1 P extraction values (a reagent complex involving HCl and NH_4F), indicating that a considerable portion of the phosphorus recovered by the aqua regia digestion consists of phosphorus less labile than recovered by the Bray-1 P extract. The Commerce pedons exhibited greater quantities of phosphorus and sulfur than the Caruthersville pedons, presumably because of the greater clay contents in the Commerce pedons. Within each pedon, the phosphorus and sulfur concentrations were largely similar with profile depth, supporting an interpretation that the phosphorus and sulfur concentrations were, to some extent, inherited during sedimentation.

Table 3. Aqua regia phosphorus and sulfur concentrations.

Caruthersville	mg/kg P Pedon #1	mg/kg P Pedon #2	mg/kg S Pedon #1	mg/kg S Pedon #2
A	550	600	130	110
C1	540	480	170	80
C2	490	460	90	90
C3	520	460	250	90
C4	450	580	90	110
C5	460	420	90	90
Commerce	Pedon #1	Pedon #2	Pedon #1	Pedon #2
A	860	990	310	290
Bw1	860	950	230	240
Bw2	780	810	160	180
Bw3	900	1,040	140	170
Bw4	800	650	170	110

The Caruthersville soil horizon phosphorus concentrations exhibit mean values of 42.6 ppm for pedon #1 and 57.2 ppm for pedon #2. The Commerce soil horizon phosphorus concentrations of exhibit mean values of 42.7 ppm for site #1 and 38 ppm for site #2. The mean phosphorus concentrations of the two pedons of the Caruthersville series and the mean phosphorus concentrations of the two pedons of the Commerce series are not significantly different. The mean phosphorus concentrations of the pooled Caruthersville pedons (49.9 ppm) and the pooled Commerce pedons (40.3 ppm) are significantly different (P=0.018).

The Caruthersville soil horizon sulfur concentrations exhibit mean values of 34.3 ppm for pedon #1 and 4.3 ppm for pedon #2 respectively. The Commerce soil horizon sulfur concentrations exhibit mean values of 3.4 ppm for pedon #1 and 3.1 ppm for pedon #2. The mean sulfur concentrations of the two Caruthersville pedons are significantly different ($P = 0.0034$), whereas the mean sulfur concentrations of the two Commerce pedons are not significantly different.

4.2. Plant tissue Analysis

Plant tissue samples were obtained to complement the soil fertility estimates. Plant tissue concentrations for the Caruthersville and Commerce soil sites are different, presumably because of the vegetation and soil fertility differences (Table 4). For the River Cane samples at the Caruthersville soil site phosphorus, calcium and sulfur were sufficient, whereas nitrogen, potassium and magnesium were slightly deficient. For the Mulberry samples at the Commerce soil site, nitrogen and phosphorus were somewhat above sufficiency, whereas potassium, calcium and sulfur were sufficient and magnesium was slightly deficient. Thus, the selected plants, at both sites, are accumulating nutrients and contributing to the maintenance of ecosystem services. It is noteworthy that both phosphorus and sulfur, for both sites, have plant tissue concentrations that are considered sufficient and not surplus.

Table 4. Plant tissue analysis of vegetation at two soil series sites (% Dry Weight).

	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	S (%)
Normal Value	2 to 3	0.1 to 0.3	1 to 2.5	0.3 to 0.5	1 to 3	0.2 to 0.5
Caruthersville						
River Cane #1	1.74	0.21	0.83	0.24	3.09	0.42
River Cane #2	1.69	0.19	0.73	0.20	2.09	0.29
Commerce						
Mulberry #1	3.99	0.27	1.77	0.25	2.53	0.21
Mulberry #2	4.14	0.27	1.76	0.30	2.87	0.25

5. Floodplain land Practices Favorable for Limiting Phosphorus Transport to the Hypoxia Zone in the Gulf Mexico

Mississippi River floodplains are important for providing a large array of ecosystem services (Petsch et al., 2022). An important ecosystem service is the capture of sediment during flood episodes. Systems of levees, stream channelization, and other engineered structures proliferate along the Mississippi River and reduce the sedimentation intensity and frequency. The sites selected for this study are annually inundated and receive annual sediment accumulations. The Caruthersville soil site is located on a meander bend and coarse-textured bedload accumulates, whereas the Commerce soil site is a backswamp environment where fine-textured material preferentially accumulates.

In both soil sites, aqua regia digestion phosphorus preferentially accumulates, and an appreciable portion of the total phosphorus pool is less biologically available than the phosphorus recovered by the Bray-1 phosphorus extract. Thus, we imply that proper watershed management that allows brief episodes of annual inundation of the Mississippi River floodplains likely limits the Gulf of Mexico hypoxia. However, we caution that prolonged flood inundation may support sufficient anoxic soil conditions to foster phosphorus desorption and release to the riverine environment.

6. Conclusion

Two soil series on annual floodplains of the Mississippi River in southeastern Missouri were selected to estimate the sulfur and phosphorus accumulation and infer whether these soil series were sequestering phosphorus and sulfur from the Mississippi River. The selected soil series were Fluvaquentic Endoaquepts and Typic Udifluvents and they were selected because of their large areal extent and their differences in soil texture.

The soils exhibited appropriate Bray-1 phosphorus concentrations and significantly greater aqua regia digestion concentrations. Plant tissue analysis of the dominant vegetation shows that phosphorus and sulfur were sufficient to support plant growth and development. Ecosystem services of these floodplain sites include the accumulation of sediment from the Mississippi River, which to some extent includes phosphorus. Preservation of these sediment collection floodplains reduces the phosphorus transference to the Gulf of Mexico and reduces the intensity of the hypoxia zone.

Author Contributions

Both authors contributed to the research design and sample collections, literature selection, narrative writing and editing, and data analysis.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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