Watershed-Scale Phosphorus Balances to Establish Reasonable Water Quality Expectations

By Heidi Peterson and Lawrence Baker

Addressing a watershed's nutrient impairment by reducing losses is an economical and long-term best management approach. When conservation practices designed to trap sediment are implemented to reduce agricultural P water quality impacts, nutrients are retained on the landscape. If improperly managed, this accumulated P can eventually leak out of the system through erosion or desorption from the soil, resulting in long-term losses of P to the stream, referred to as legacy P. Compiling a watershed-scale nutrient balance enables watershed managers to identify production areas where P use efficiency strategies could be incorporated into conventional conservation planning. This produces a more holistic approach to understanding nutrient cycling across the landscape, thereby enhancing prospects for meeting P loss reduction goals for water quality improvement.

Agricultural System Phosphorus Balance and Use Efficiency

A watershed's P mass balance for agriculture could be calculated on an annual basis using the general equation:

$$\Delta \text{ P (Storage)} = \text{P Inputs - Deliberate P Outputs - Stream P Exports}$$

where Δ P is the annual change of P stored in the watershed.

Inputs to consider would include any feed, livestock, manure, or fertilizers brought into the watershed. Deliberate outputs may include meat or dairy products, harvested crops not consumed as livestock feed, and livestock mortalities that are exported out of the watershed to landfills or rendering plants. Manure may be considered a deliberate output if it is not all applied to crops within the watershed. Stream exports are the P losses out of the watershed through waterways. When P inputs into the watershed are greater than deliberate P outputs, either Δ P increases and the soil P within the watershed is increasing, or P is running off the landscape and into the watershed's waterways.

Another way to look at this system balance using deliberate P outputs and inputs is by calculating the P use efficiency (PUE).

$$\text{Agricultural System PUE} = \frac{\text{Deliberate P Outputs}}{\text{P Inputs}}$$

An agricultural system with high PUE results when deliberate P outputs exceed P inputs and PUE > 1.0. When this occurs, assuming all other management practices remain the same, watershed Δ P and STP should decrease with time, eventually leading to declines in stream P exports due to reduced contributions from surface P runoff. If more P is brought into the watershed than exported, the agricultural system PUE < 1, resulting in increased P storage and STP concentrations, which could lead to increased stream P concentrations. When the system is in balance and P inputs are equivalent to P outputs, PUE = 1.0. Depending on the purpose of the calculation results, the defined inputs and outputs will vary. When looking at efficiency from a water quality perspective, the outputs should include any P that is removed from the watershed, whether it is a product, reusable by-product, or waste material. For a producer's purpose

Lisa Gjersvik Photo

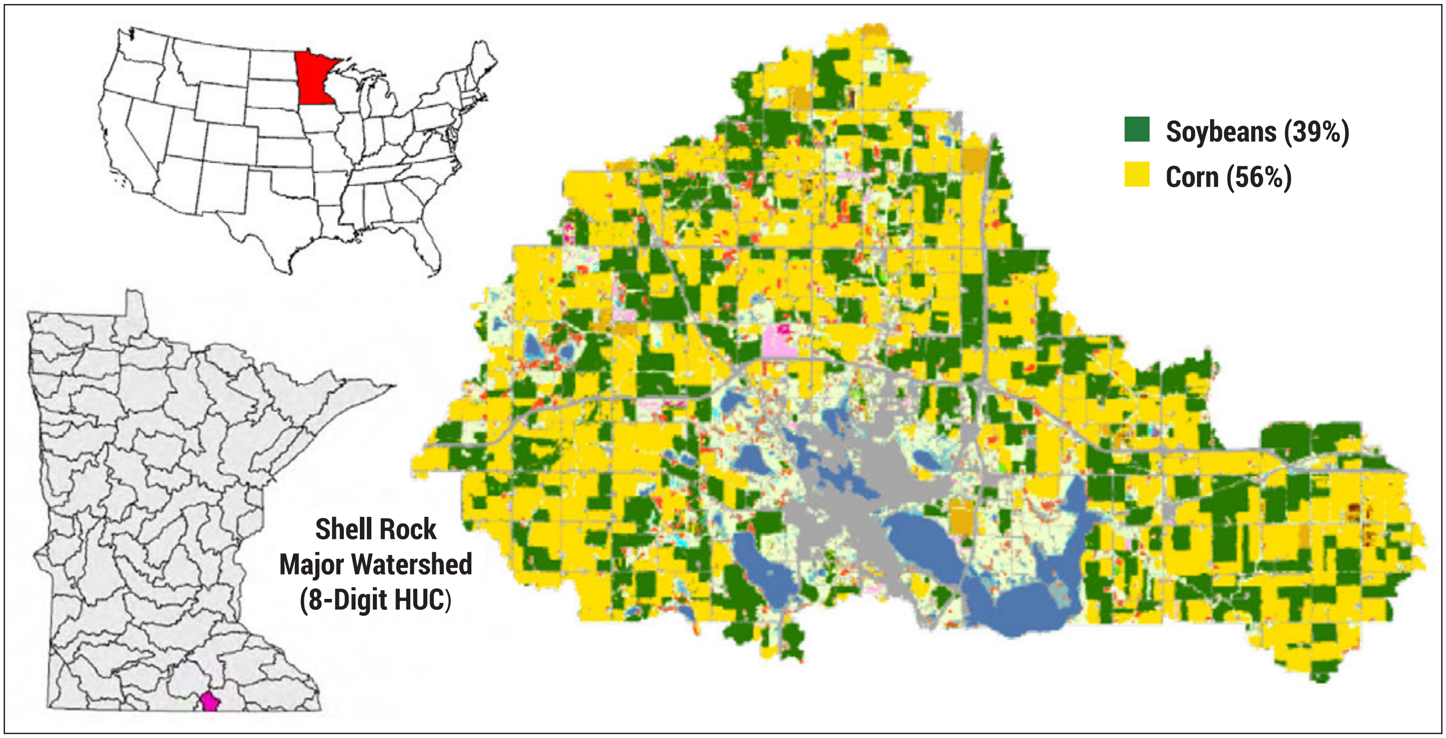
Aerial view of farmland surrounding a creek within the Albert Lea Lake watershed in southern Minnesota.

Integrating watershed P balances into conventional conservation planning provides a holistic approach to understanding the nutrient cycling across the landscape, critical for meeting load reduction goals for water quality improvement. To maintain high P use efficiency while ensuring successful crop yields, soil sampling should be encouraged to utilize the available P in areas where additional inputs are not necessary, while ensuring that STP remains above the crop's critical concentration.

KEYWORDS:
phosphorus balance; phosphorus use efficiency; watershed; Minnesota

ABBREVIATIONS AND NOTES:
P = phosphorus; STP = soil test phosphorus; ppm = parts per million.

https://doi.org/10.24047/BC102125



Albert Lea Lake watershed in Freeborn County, Minnesota (USDA, 2011) drains south into the Cedar River, a tributary of the Iowa River, which flows to the Mississippi River.

of determining how efficient a specific cropping or livestock system is at utilizing P through growth and development, into a finished or value-added product, the P outputs would not include any landfilled waste.

For example, IPNI's NuGIS database (IPNI, 2012) provides regional PUE estimates using fertilizer and manure as the P input, and the P removed by the harvested crop is the P output. This calculation allows a producer to quantify how much P is being taken out of the system in relation to the amount applied and can be useful over the long-term when compared to STP. Data from NuGIS indicates increasing crop PUE for the U.S. Corn Belt states from 0.81 in 1987 to 1.13 in 2010, likely attributed to increased crop P removal from higher yields with reduced P fertilizer inputs. When PUE > 1.0 and crop P uptake is greater than the quantity applied, STP concentrations will decline, as crops utilize the available P (Fixen et al., 2010). This has been demonstrated across the Corn Belt states, where median STP concentrations declined from 29 ppm in 2005 to 23 ppm in 2015 (IPNI, 2015). Research has demonstrated that as STP concentrations decline, there is also a consistent relationship in reduced dissolved P runoff losses (Vadas et al., 2005).

Table 1. Albert Lea Lake watershed 2010 crop P use efficiency (PUE) data.

	Calculated total crop removal of P	Calculated total applied P	Crop PUE
	--------- lb/yr ---------		
Alfalfa	18,916	646	29.3
Barley	692	739	0.9
Corn	1,085,265	852,534	1.3
Corn-*Sweet*	56,851	20,884	2.7
Grasses-*Hay*	10,651	9,458	1.1
Oats	273	243	1.1
Rye	9	15	0.6
Soybeans	445,435	23,415	19.0
Wheat	223	401	0.6
Total	1,618,312	908,333	1.8

Phosphorus Balance Case Study from a Minnesota Watershed

Albert Lea Lake watershed is a highly productive agricultural watershed in south-central Minnesota, at the headwaters of the nutrient impaired Shell Rock River watershed. Local stream monitoring has indicated that a high proportion of the total P load is soluble P, originating from subsurface drainage systems; however, watershed planning has focused primarily on implementing practices that re-

Table 2. Phosphorus use efficiency (PUE) of livestock systems within the Albert Lea Lake watershed.

	P input[1]	Product P output[2]	PUE
	----- tons (U.S.)/yr -----		
Beef	18.1	5.1	0.28
Pork	90.2	49.9	0.55
Dairy	3.6	1.3	0.37
Turkey	22.7	12.3	0.54

[1]P inputs included young animals, feed and supplements.
[2]P outputs included livestock products, manure and rendered mortalities.

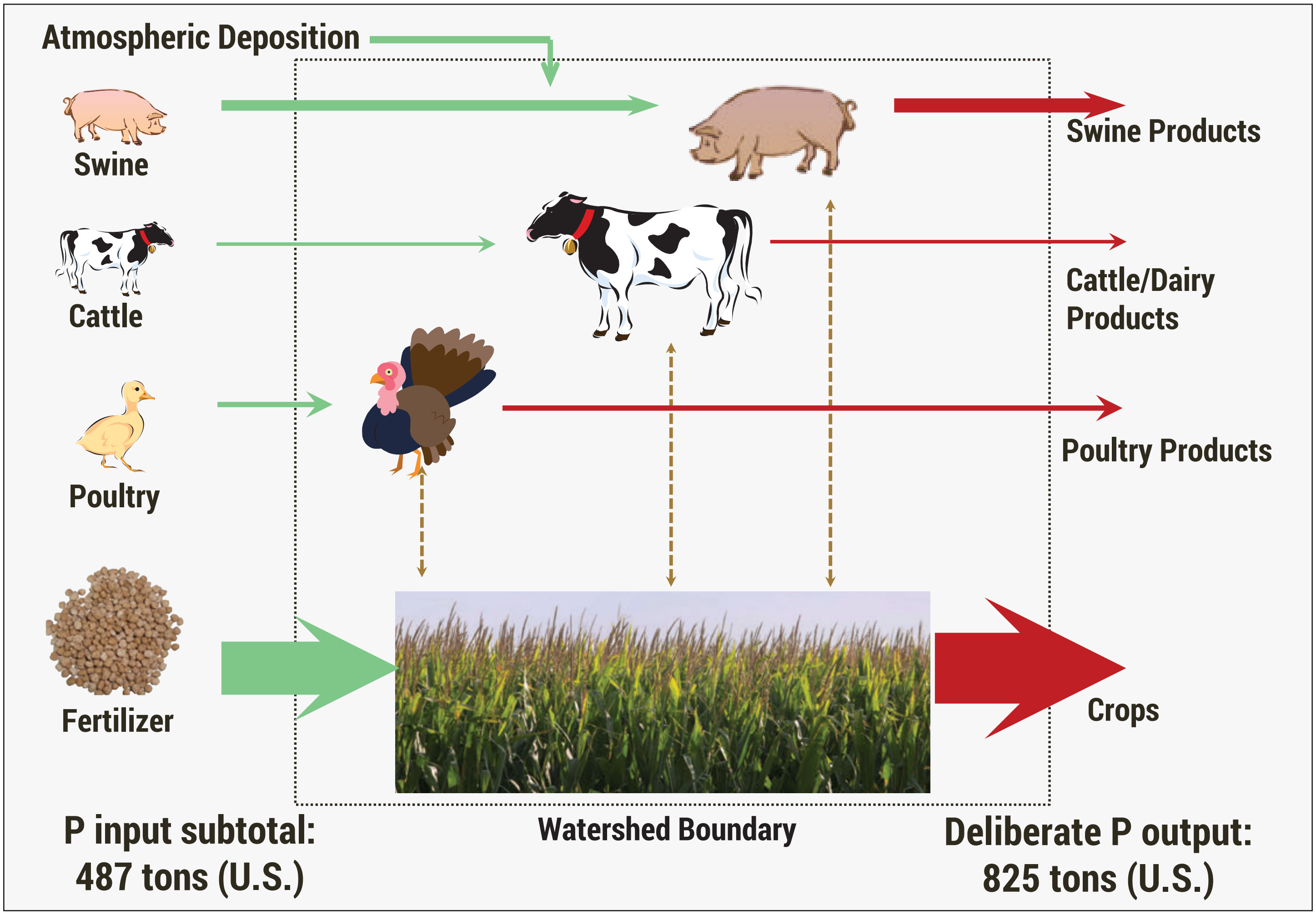


Figure 1. Annual agricultural P inputs to, outputs from, and transfers within the Albert Lea Lake watershed, resulting in a watershed P balance of 1.7. Arrow size represents the relative proportion of watershed inputs or outputs.

duce particulate P rather than improving agricultural nutrient management (MPCA, 2012).

A comprehensive agricultural system P balance was computed for the approximately 93,160-acre watershed using site-specific crop and livestock management data acquired through personal interviews, surveys, feedlot permits, and site visits together with published resources (Peterson et al., 2017). The data was computed using the Agricultural P Balance Calculator developed by Peterson and Baker (2014). Total crop PUE was 1.8 (**Table 1**), which is consistent with the 1.1 to 2.0 watershed range estimated by IPNI for 2010 (IPNI, 2012).

Most of the agricultural fields in the watershed operate under a corn and soybean rotation, applying P only during a corn planting year. Phosphorus removal by the crops increased faster than P inputs, resulting in improved efficiency. The agricultural system PUE was 1.7, indicating that more P was exported from the watershed as agricultural products than brought in as fertilizer, implying that crops were utilizing available P from watershed soils (**Figure 1**; Peterson et al., 2017). The watershed has low livestock density (0.08 animal units/A), allowing farmers to spread manure based on STP concentrations (**Table 2**).

Although the agricultural system PUE was > 1, stream P export was 5% of the annual watershed P input, exceeding the target P load for lakes within the watershed. Since deliberate P outputs are greater than P inputs within the watershed, this suggests that the root of the problem is likely something other than a general P input surplus. Inefficient P application practices with a combination of improper timing and placement could be resulting in high runoff losses. It could also be an indication that areas within the watershed with disproportionately high STP concentrations from legacy P are contributing P losses through erosion or desorption. Bray P results from southern Minnesota soil samples indicate that over 60% of the samples analyzed exceeded optimum STP concentrations, with approximately 40% of sam-

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Soil P testing allows producers to maintain optimum STP concentrations while reducing their water quality impacts without jeopardizing crop yield.

ples twice the critical concentration. To maintain high PUE while ensuring successful crop yields, soil sampling should be encouraged to utilize the available P in areas where additional inputs are not necessary, while ensuring that STP remains above the crop's critical concentration. This will ensure that crop PUE > 1 until the STP is reduced to the optimum range. In other areas of the watershed where manure or fertilizer P is applied, producers could adopt management practices which have been shown to reduce soluble P losses, such as the incorporation of manure through light tillage or variable rate application technology.

If the Albert Lea Lake watershed continues to operate in a P balance deficit, STP concentrations should decline, resulting in decreases in runoff P, especially when integrated with the adoption of conservation practices. Quantifying how quickly this reduction in stream P export occurs would require ongoing annual watershed P balance studies with long-term soil and water quality monitoring. The availability of soil P is dynamic and through mineralization of organic matter and desorption from soluble minerals, the soil solution can maintain equilibrium and continue to supply plant available P depending on soil characteristics and management including microbiology, tillage, and moisture levels.

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Summary

Incorporating a P balance approach as a first step in watershed planning provides watershed managers with a holistic perspective into the agricultural system to determine the efficiency of livestock and cropping systems. Producers within the watershed could improve the watershed agricultural system PUE by optimizing their crop or livestock PUE. This could be done by keeping the crop PUE > 1 where STP concentrations exceed the recommended optimum range, keeping the crop PUE < 1 where STP concentrations are below the recommended optimum range, or maintaining crop PUE = 1 where STP is at the recommended optimum range. If cropping and livestock PUEs are optimized by producers, then watershed and conservation organizations could target the implementation of conservation practices in areas where erosion losses dominate the P input. **BC**

Acknowledgement

This article is adapted from Peterson, H.M. et al. 2017. Agricultural Phosphorus Balance Calculator: A tool for watershed planning. J. Soil Water Cons. 72:395-404. http://doi:10.2489/jswc.72.4.395

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