THE RELATIONSHIP BETWEEN
SOIL PHOSPHORUS CONCENTRATIONS AND WATER QUALITY

LINKING FARM PHOSPHORUS LOAD AND HYDROLOGY

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Introduction

“Variability in runoff volume and erosion as a result of climatic, topographic, and agronomic factors plays a larger role than soil-test P in determining the amount of P losses from agricultural land.” (Sibbeson and Sharpley, 1997).

Sibbeson and Sharpley have part of the equation correct when they allude to the important influence of hydrology in determining the amounts of P lost from agricultural land. This paper emphasizes the importance of starting the analysis with the effect of P on aquatic biology and working upstream to consider the entire effect of the farm on surface water quantity and quality.

As we know, increased population density and demands on soil and water resources have led to intensified efforts to improve surface and groundwater quality throughout the US.

Both phosphorus (P) and nitrogen (N) are important in this context. Phosphorus, which moves very little in most soils except at very high concentrations, is primarily considered a surface water pollutant, delivered in runoff water. High P leads to rapid growth of aquatic vegetation, causing problems for aquatic life and drinking water supplies. In some situations, increases in N supply to surface waters may also enhance aquatic plant growth.

For groundwater, nitrate-N contamination is most often considered the prime concern, due to toxicities related to direct consumption of high-nitrate water by humans.

Farmers add P to crop fields to increase crop growth and economic yield. The same P entering surface water systems can lead to excessive plant growth.

This paper begins by comparing the bioavailable P requirements of terrestrial, land-based plants with those of aquatic plants. This comparison can be used to develop new strategies, and to assess existing strategies, for maintaining adequate soil P for optimal crop growth while minimizing excess P in surface water. It also discusses the application of the “whole farm effect” analysis for evaluating the total impact of the farm on P bioavailability in water.

The basic questions to be addressed are those of economics and environment, NOT mutually exclusive:

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Can cropping systems maintain adequate bioavailable soil P for economically viable crop growth, without increasing bioavailable P downstream to excessive concentrations?

Definitions:

Terminology in this area is often inconsistent and garbled, so for the purposes of this presentation some important terms are defined below. **Disclaimer:** definitions may vary from those offered below, depending upon the author’s perspective. This is especially true in contrasting soil science/terrestrial analyses with limnology/aquatic analyses of bioavailability.

Like plant growth, the term “bioavailability” describes a dynamic process. For practical purposes we simplify it with static chemical analyses, like soil extracts, but it is fundamentally the **rate of nutrient supply to the plant.** As such, it involves all the physics, chemistry, and biology in the plant’s environment, working through time.

General considerations of bioavailable P

**Components of bioavailable P, from the plant perspective, include the following:**

- **Concentration** in solution around the absorbing cell; **Rate of supply** to solution around the cell; **Time** over which uptake occurs; **Total quantity supplied**

**Concentration** in solution around the absorbing cell:

With minor exceptions, P appears to be taken up through the cell membrane as some form of the orthophosphate ion (ortho-P: $\text{H}_2\text{PO}_4^-$; sometimes as $\text{HPO}_4^{2-}$). The **concentration** of ortho-P at the membrane surface determines the rate of P uptake, and consequently the growth rate of the plant.

**Rate of supply** to solution around the cell:

Rapid uptake of ortho-P in the area around the absorbing membrane lowers the concentration on ortho-P and therefore decreases the rate of uptake. The concentration may be renewed in several ways:
- diffusion from a distance;
- mass flow/turbulent mixing of solution from a distance;
- release/desorption from iron and aluminum oxides adjacent to the cell;
- dissolution of phosphorus compounds, especially calcium –P’s, adjacent to the cell; and
- decomposition of organic P molecules adjacent to the cell.

Mycorrhizal fungi, beneficial root associates, decrease the solution concentration necessary for optimal plant growth because the hyphae permeate the soil and lower the distance over which diffusion has to occur. This means, effectively, better plant growth at lower solution P concentrations.

**Time over which uptake occurs:**

The longer the plant is growing, the more P it will accumulate.
Total quantity supplied:
This is the total amount of P in the system (soil, sediment, water) that can reach the plant absorbing surface cell as ortho-P.

All these processes operate in soils, sediments, and the water column. However, their relative importance varies with the specific system in which they are occurring.

Soils
Bioavailable P is often defined as the quantity of P that a plant can take up during the growing season. This includes the following forms:
- Ortho-P in soil solution (instantly available for uptake after diffusion to the root);
- P sorbed on iron and aluminum oxides in soils (available after it desorbs into soil solution and diffuses to the root);
- P precipitated in calcium compounds (available when it dissolves, enters soil solution, and diffuses to the root); and
- organic P (available after the molecule decomposes and the ortho-P released diffuses to the root).

In all cases we are concerned with the rate at which P diffuses to the surface of the root/mycorrhizal fungus hypha, as affected by the chemistry, physics, and biology of the soil around the root.

Bioavailable P in surface water:
Sediment: In shallow water, many aquatic plants are rooted in the sediments and obtain much or most of their nutrients from the sediments rather than from the water column.

Sediment bioavailability issues are much like the soil, except for lack of airspaces and consequently a greater chance of anaerobic conditions occurring. For P availability, this is most important where a significant fraction of the P occurs as iron phosphates, because iron will be reduced and dissolve under anaerobic conditions, releasing P into the solution.

This P can then diffuse as ortho-P out of the sediments and into the water column, where it is immediately bioavailable.

Water column: Particles play a very small role in the water column, although release of P from bottom sediments can be critically important. Suspended organic matter may decompose and release ortho-P into the water column. Diffusion is much less important because the system is somewhat turbulent and well-mixed. Therefore the overall concentrations can be lower and still maintain adequate rates of uptake.

LOAD or CONCENTRATION? THE “WHOLE FARM EFFECT”
How do we relate the P coming from the farm to the adverse effects of P on aquatic vegetation, remembering that the direct response of suspended aquatic plants is to the concentration of ortho-P in the surface water body?

Agricultural P inputs have been expressed in terms of either load – e.g., lbs P/acre/year; or concentration in the runoff water, e.g., mg/L. Do we worry most about the P Load or the P Concentration in evaluating the impact of agricultural soil P on surface water quality?

We worry about both, by evaluating the “whole farm effect” on the quality of water receiving bodies below it

The “whole farm effect” on surface water P concentration:
Divide the LOAD of bioavailable/suspended and dissolved P coming from the land (lbs P/acre, for instance) by the VOLUME or mass of water entering the water body (millions of lbs water/acre, for example). Dividing lbs P/acre by millions of lbs of water/acre gives average parts per million (ppm) P in the water (mass basis). This is the same as mg P/L or mg P/kg water.

This may best be represented using the example below:
Let us express the concentration of P at any point in a stream based on the contributions of land (both P and water) to the concentration in the water body.

I will define a term that describes the overall impact of the farm on P bioavailability in the water:

The “whole farm effect” on surface water P concentration:
Divide the LOAD of bioavailable/suspended and dissolved P coming from the land (lbs P/acre, for instance) by the VOLUME or mass of water entering the water body (millions of lbs water/acre, for example). Dividing lbs P/acre by millions of lbs of water/acre gives average parts per million (ppm) P in the water (mass basis). This is the same as mg P/L or mg P/kg water. We will term this the “farm effect”.

What does the aquatic ecosystem need to be non-eutrophic, that is, without excessive nutrients and associated plant growth?
Studies suggest that as long as total P concentrations in a receiving lake stay below 0.030 ppm P, water bodies will not become eutrophic (see Newton and Jarrell, 2000, below). Streams and estuaries may tolerate higher concentrations, up to 0.050 ppm total P.

**Question:** What concentration of total P in runoff will be acceptable in keeping a farm from increasing the concentration of P in the stream to values above 0.030 ppm P?

**WATER VOLUME YIELD FROM AGRICULTURE:**
How much water (VOLUME) does an acre of Wisconsin farmland release per year?
Assume annual precipitation of 40” of rainfall.
Assume
\[
\begin{align*}
\text{Evapotranspiration} &= 19”/\text{year} \\
\text{Runoff} &= 1”/\text{year} \\
\text{Subsoil groundwater recharge (below crop root zone)} &= 20”/\text{year}
\end{align*}
\]

This is a total of 21” of water that enters surface water bodies from the farm.

This is equivalent to about 2.1 million liters of water per acre that the farm is contributing to the surface water, assuming no irrigation-scale pumping.

**LOAD**
How much load can this farm generate and still keep the “farm effect” from exceeding 0.030 ppm P?

Total load:
In 2.1 million L of water containing 0.03 mg total P/L, there is a total of about 60 g P.

If the baseflow water contains 0.02 mg total P/L, baseflow contributes a total of 40 g of P, leaving a margin of 20 g P/acre that can be lost in the surface runoff.

For a surface runoff equivalent to 1” of water, or 0.1 million L of water, this allows up to 0.2 mg total P/L in the runoff water. Typical concentrations of total P in runoff from agricultural and pasture fields range from less than 0.2 mg P/L to greater than 1.5 mg P/L.

If the farm is able to decrease runoff to about 2.5% of total precipitation, the average P concentration in that runoff can be as high as 0.40 mg P/L without adversely affecting the quality of water passing that point. Of course, eliminating runoff eliminates the load. Typical concentrations of total P in runoff from agricultural and pasture fields range from less than 0.2 mg P/L to greater than 1.5 mg P/L.

An important concern with this analysis is determining exactly how much of the P leaving the farm is bioavailable in a reasonable timeframe, e.g., 1-3 years. Most of the organic P probably is. Some of the inorganic P may be in such insoluble forms that it is not bioavailable, and should not be included in this analysis. And how much of the runoff P is trapped before it leaves the field or farm? Measuring and regulating based on total P provides a worst-case scenario of the impact of agricultural runoff on surface water P concentrations.

Recharge within a given field will vary depending on the crop yield. Woodlots and pastures may transpire more water but generate less runoff P load. Cropland typically generates more runoff, but because of water use patterns it may result in more groundwater recharge as well.
Some related management strategies:

**Increased infiltration:**
- Re-direct waters through the subsoil prior to discharge into surface waters as baseflow. Increase infiltration of rainfall and snowmelt, which lowers runoff P in both solid and dissolved forms. It also increases baseflow of low-P subsoil water which dilutes high-concentration, low-volume inputs of P from runoff, because subsoils are typically lower in P concentrations than surface soils. Except for cold and/or dry deserts, most natural environments have little surface runoff from soils directly into surface water.

**Total environmental impact of agriculture:**
- Give farms credit for the high-quality (low P) and quantity of water they provide to ecosystems through baseflow, counting all land uses on the farm; give incentive for more efficient water use practices which result in greater water yield during critical periods like summer.

**Erosion control:**
- Stop organic and inorganic particles from entering surface waters. Organic particles include those from manure and crop residues, and inorganic particles include soil clays.

**Amendment rates:**
- Add P based on crop needs, not soil capacity. The latter is a short-term strategy that will have to be changed eventually.

**Plant uptake efficiency:**
- Encourage deep rooting and effective mycorrhizal fungi; this allows the plant to yield economically in soils with low solution P concentrations.

**Monitoring methods:**
- Directly measure dynamic properties of P in soils that relate to its mobility and bioavailability, because these properties determine the potential for soil P to become an environmental pollutant. Existing soil tests were designed for crop production, not environmental hazard analysis.

**Timing of water/phosphorus supply:**
- As much as possible, delay baseflow release of subsoil water into the summer. Tile drains are giant macropores that prematurely drain water from the land, and lower mid-summer baseflow from shallow aquifers. Consider drainage control valves on tile lines, which may help conserve water for crops during dry springs as well.

**Low-P water from upper watershed:**
- Acknowledge the value of low-P water from the watershed above the farm, and encourage programs that maintain or even enhance water quality in the upper watershed.

**Annotated bibliography:**
