Plant Availability and Environmental Significance of Phosphorus in Land-Applied District Biosolids

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Kuldip Kumar
Albert Cox
Acknowledgements

- Section 123 Technicians and Chemist
  - Field and greenhouse work, lab analyses etc.
- Rosalie Swango and other M&O staff at Fulton County
  - Field and greenhouse work, lab analyses etc.
- Analytical Labs Division
  - Analyses
But Phosphorus is a Good Thing

Humans and Animals
- Essential ingredient of all cell protoplasm, nervous tissue, and bones
- Part of DNA material
- Primary factor in energy distribution (ATP)

Plants
- An essential plant macro-nutrient
- Formation of sugars and starches and conversion of solar energy into chemical energy
- Stimulation of early growth and root formation, and promotes plant hardiness and seed production
So What’s the Concern?

- Increase P concentrations marked as primary culprit in eutrophication of surface water causing:
  - Reduce lake water quality, cause fish kills and algal blooms
  - And ultimately decrease recreational and economic opportunities
  - More attention to non-point source (e.g. farmland) pollution in recent years.
Phosphorus in Wastewater Treatment Process

- Fertilizer runoff
- Detergents
- Excreta

Influent

Pretreatment

Primary Treatment

Biological Treatment

Effluent

Sludge Processing

Biosolids

Land Application (fertilizer)

Over 60% of District’s 180 dry tons/yr
N-based Application Rates

- N balance
- Excess P

P-based Application Rates

- N deficit
- P balance

Biosolids Content
Crop Requirement
Phosphorus

Critical Value for Crop Yield

Critical Change Point for Environmental Effects

Reactive P in Soil

Soluble P in Drainage & Runoff
Efforts to Minimize Agricultural P Impacts

P-Based Nutrient Management

- USDA-NRCS 590 Standard: P-based plans based on site characteristics and vulnerability of water bodies

  - Options

- USEPA – Confined Animal Feeding Operation (CAFO): Nutrient Management Plan

  According to IEPA: CAFO rule may form basis of P-based rate biosolids rule in Illinois

  - No application where soil test P >300 lbs/acre (150 mg/kg)
  - Only amount P to meet crop needs (single or multiple seasons)
  - Buffer: 100 ft from surface water
How Might P-based Application Affect District Biosolids Farmland Program?

- Need more land for application
  - Longer distance, higher costs
  - Scenario: To utilize 100,000 dry tons/yr
    At current N-based rate of ~10 tons/ac, we need 10,000 acres
    At P-based (~2.5 dry tons/ac), we’ll need ~40,000 acres
- Farmers will need to apply supplemental N fertilizer
- Difficult and probably impractical to accurately apply <5 dry tons/ac
<table>
<thead>
<tr>
<th>Soil Test P Range (lbs/ac)</th>
<th>No. of Fields</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;40</td>
<td>20</td>
<td>Low</td>
</tr>
<tr>
<td>40 - 50</td>
<td>8</td>
<td>Low</td>
</tr>
<tr>
<td>60 - 80</td>
<td>5</td>
<td>High</td>
</tr>
<tr>
<td>&gt;80</td>
<td>60</td>
<td>Very High</td>
</tr>
<tr>
<td>&gt;300</td>
<td>7</td>
<td>Prohibited</td>
</tr>
</tbody>
</table>

Average for fields at <300 lbs/ac = 114 lbs/ac
## Typical Characteristics of MWRD Biosolids Controlling Fate of P

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Al (%)</td>
<td>2.0 – 3.0</td>
</tr>
<tr>
<td>Total Fe (%)</td>
<td>2.5 – 4.5</td>
</tr>
<tr>
<td>Water Soluble P (1:25 solid:water), mg/kg</td>
<td>60 – 120</td>
</tr>
<tr>
<td>Total P (%)</td>
<td>1.8 – 2.5</td>
</tr>
<tr>
<td>(lbs P/ton)</td>
<td>36 - 50</td>
</tr>
</tbody>
</table>
IEPA’s Top Questions
District & IEPA Collaborative P Research

1. Could a P coefficient be developed which would predict what portion of the total P contained in biosolids would be available for plant uptake?

2. Is there a residual availability of P over time similar to the residual contribution of N over 5-year of application? If Yes? How much?

3. How much of a reduction in P runoff would occur if biosolids were incorporated rather than surface applied?

4. What is the appropriate buffer zone to limit P runoff? The Agency is tentatively proposing a 100-ft buffer from surface water. Is this enough, too much or too little?
Bioavailability: Greenhouse Study – Albert Cox

- A coefficient can be used to account for lower bioavailability of biosolids P compared to fertilizer P, with respect to soil test P and plant uptake
- Residual biosolids P in soil is released slowly over time

Bioavailability: Field Studies – Guanglong Tian

- Confirm findings of greenhouse study
- How data can be used to develop P-based guidelines

P Runoff Biosolids Studies – Kuldip Kumar

- Runoff potential of biosolids P
- Length vegetative reasonable to protect surface waters
Imminent P-based Biosolids Land Application Rule

Is the District’s Farmland Application Program at Risk?
Bioavailability of Biosolids P
Greenhouse Study
Greenhouse Study: Methods

- **Soil:** P-deficient sandy soil (STP = 2.5 mg P/kg (5 lb/ac))
- **3 P sources**
  1. TSP (chemical fertilizer)
  2. Class A Air-dried biosolids
  3. Class B Centrifuge cake biosolids
- **6 targeted P rates:** 0 – 300 mg P/kg soil
- **4 Replicates**
- **Crop:** Alternating wheat & perennial rye
  - Clip foliage every 30, then regrow or reseed
  - Total of 18 crops
Relief Workers harvesting wheat Foliage

So what you doing next summer, 2011?

I don’t know!!
Not at the District!
Greenhouse Study: Methods

Soil Analyses (after every two crops)
- Soil Test P – Bray 1 method
- Water soluble P (WSP)
- Total P

Plant Analyses
- Weigh foliage to determine dry matter (DM) yield
- Determine P conc. in tissue

Calculations
- P uptake = DM x P conc.
- Immediate availability = cum P uptake in first 3 crops
- Total availability = Cum P uptake in all 18 crops
How Did P Sources Change STP and WSP?

Bray 1 Soil Test P

Water Soluble P

S = 0.74
S = 0.60
S = 0.55
## How Much P is Needed to Increase Bray 1 Soil Test P by 1 Pound?

<table>
<thead>
<tr>
<th>Initial STP (mg P/kg)</th>
<th>P Source</th>
<th>Immokalee Sand</th>
<th>Waseka Sand</th>
<th>Drummer clay loam</th>
<th>Fulton Co. clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>TSP</td>
<td>1.3</td>
<td>1.2</td>
<td>1.6</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Biosolids</td>
<td>1.7</td>
<td>3.6</td>
<td>7.9</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Data from 2002 lab study
How Many More Applications before IEPA Limit?

Ave. STP in farmland soils = 114 lbs/ac

STP (lbs/ac)

300
250
200
150
100
50
0

IEPA says: No application above here

Window = 186 lbs/ac

100 lb STP ~ 800 lb Biosolids P
Each application ~ 400 lbs P
100 lb STP ~ 2 applications
No. Applications ~ 4

Ave. STP in farmland soils = 114 lbs/ac
Cumulative P Uptake in Three Consecutive Foliage Clipping: Immediate Plant Availability

Typical P applied at N-based Biosolids rate

Relative effectiveness
TSP = 100%
Class A = 43%
Class B = 30%
Draw Down of Soil Test P

How long does it take to get back?

P Added = 200 mg P/kg (400 lbs/ac)

P Added = 300 mg P/kg (600 lbs/ac)

IEPA STP Limit
150 mg/kg
### Bray 1 Soil Test P in Top Layer of Pots After 18 Cycles of Cropping

<table>
<thead>
<tr>
<th>P Rate (mg P/kg)</th>
<th>Class A (mg P/kg)</th>
<th>Class B (mg P/kg)</th>
<th>TSP (mg P/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>25</td>
<td>3.1</td>
<td>3.5</td>
<td>1.7</td>
</tr>
<tr>
<td>50</td>
<td>5.5</td>
<td>6.8</td>
<td>1.5</td>
</tr>
<tr>
<td>100</td>
<td>20.1</td>
<td>14.9</td>
<td>2.1</td>
</tr>
<tr>
<td>150</td>
<td>45.1</td>
<td>34.3</td>
<td>3.6</td>
</tr>
<tr>
<td>200</td>
<td>67.1</td>
<td>52.7</td>
<td>6.1</td>
</tr>
<tr>
<td>300</td>
<td>116.6</td>
<td>81.8</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Treated = Soil + P Sources
Untreated layer
**Water Soluble P in Bottom Layer of Pots After 18 Cycles of Cropping**

<table>
<thead>
<tr>
<th>P Rate (mg P/kg)</th>
<th>Class A (mg P/kg)</th>
<th>Class B (mg P/kg)</th>
<th>TSP (mg P/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>25</td>
<td>1.28</td>
<td>1.65</td>
<td>1.72</td>
</tr>
<tr>
<td>50</td>
<td>2.36</td>
<td>2.33</td>
<td>2.71</td>
</tr>
<tr>
<td>100</td>
<td>3.21</td>
<td>3.45</td>
<td>5.21</td>
</tr>
<tr>
<td>150</td>
<td>5.64</td>
<td>5.13</td>
<td>10.23</td>
</tr>
<tr>
<td>200</td>
<td>7.38</td>
<td>6.49</td>
<td>15.78</td>
</tr>
<tr>
<td>300</td>
<td>7.35</td>
<td>6.42</td>
<td>26.38</td>
</tr>
</tbody>
</table>

Treated = Soil + P Sources

Untreated layer

Leaching

12”
Cumulative P Uptake in 18 Consecutive Foliage Clipping: Long-term Plant Availability

- P Rate (mg P/kg soil)
- P Uptake (mg P/pot)

Graph showing the relationship between P Rate and P Uptake for different classes and TSP treatments.
How Might P Removal Affect Biosolids P?

Effect of Chemical P Removal on P in Biosolids from Pilot Study at Egan WRP

- Total P in biosolids (mg/kg)
- Bray 1 P in biosolids (mg/kg)
- Water extractable P in biosolids (mg/kg)
Bioavailability: Greenhouse Summary

1. Bioavailability: Short-term (i.e. first season)
   - Bioavailability of biosolids P is less than 50% compared to TSP fertilizer
   - Biosolids less effective than TSP to increase STP
   - To raise STP by 1 lb biosolids P required is ~8 lbs in clay loam soils and ~4 lbs in sandy soils

2. Bioavailability: Long-term
   - Bioavailability of biosolids P is similar to TSP due to slow availability of residual in soil
   - Draw down of STP over time is slower for biosolids P than for TSP
Over To Tian
Confined Animal Feeding Operations
“Meat Factories”
USDA-NRCS 590 Standard
Navigating the Phosphorus Traffic

<table>
<thead>
<tr>
<th>Field P Rating</th>
<th>Determination of P Application Rate</th>
<th>Biosolids Land Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>Prohibited</td>
<td>Prohibited</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>P-Based</td>
<td>NOT Practical</td>
</tr>
<tr>
<td>LOW</td>
<td>N-Based</td>
<td>Feasible</td>
</tr>
</tbody>
</table>
So What’s Your Contribution?
What we eat, drink, and use

I am what I ate, and I scared – Bill Cosby

High P Diet

Low P Diet

Vegetarian/Vegan

Tax break?
Fulton County
Field Study
Experimental design

Design: Randomized complete block

Replication: Four

Treatments (P levels in kg P ha\(^{-1}\)):

<table>
<thead>
<tr>
<th>Control (no P)</th>
<th>163: Biosolids-P vs. P fertilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>325: Biosolids-P vs. P fertilizer</td>
</tr>
<tr>
<td></td>
<td>488: Biosolids-P vs. P fertilizer</td>
</tr>
<tr>
<td></td>
<td>650: Biosolids-P vs. P fertilizer</td>
</tr>
</tbody>
</table>
Fulton Country, W. Illinois

- One application (10/2005): biosolids and Triple SuperPhosphate (TSP, P fertilizer)
- Initial soil Bray-1 P: 13 ppm
- pH 5.8
- O.C.: 2%
- Soil texture: Silty clay loam
Agronomic effectiveness

**P uptake by corn (kg ha\(^{-1}\))**

- No 163P 325P 488P 650P
- Biosolids
- P fertilizer

**Corn grain yield (Mg ha\(^{-1}\))**

- No 163P 325P 488P 650P
- P rate (kg ha\(^{-1}\))
Dynamics of soil Bray-1 P and effectiveness of biosolids in raising it

Biosolids $\approx \frac{1}{2}$ TSP
Dynamics of soil water extractable P and the effectiveness of biosolids in raising it.

Biosolids = $\frac{1}{4} - \frac{1}{3}$ TSP
Recovery of P at 3 years after the P application
Long-term data support less leaching of P from biosolids

Control: $y = 0.0005x + 0.085$  $R^2 = 0.14$  $P < 0.01$

Biosolids: $y = 7E-06x + 0.0985$  $R^2 = 1E-04$  NS

Control

Biosolids

Ground Water

Total P (mg L$^{-1}$)

Months after application began
Biosolids Fe/Al add to soil P fixation capacity

- \( \text{Fe(OH)}_n^+ \)
- \( \text{H}_2\text{PO}_4^- \)
- Fe-P complexes
  Adsorption and co-precipitation
Amorphous Fe oxides increase along the biosolids application
<table>
<thead>
<tr>
<th>Residual effects: Cropping years to return to initial P level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Bray-1 P</td>
</tr>
<tr>
<td>(agronomic effectiveness)</td>
</tr>
<tr>
<td>P fertilizer &lt;4 yr</td>
</tr>
<tr>
<td>Biosolids &gt; 4 yr</td>
</tr>
</tbody>
</table>
Surface water at Fulton County long-term biosolids application watershed

[Graph showing the total phosphorus (mg L⁻¹) in surface water over months after applications began for control and biosolids treatments.]
Conclusions

• Possible:
  N-based biosolids land application

• Not possible:
  yearly repeated application
Recommendations for biosolids land application program

A Nitrogen-Based 5-Year Rotation

400 = 200
Potentials of farmland in Chicagoland for biosolids use

- South block: 30 X 40 mile
- West block: 30 x 40 mile
- Crop land: 400k ha
- MWRD biosolids farmland: 100k Mg yr\(^{-1}\)
- Biosolids 20 Mg ha\(^{-1}\):
- Land needed for biosolids: 1%
- Rotate every 5 yr, only use 5 % land
But Phosphorus is a Good Thing

Humans and Animals
- Essential ingredient of all cell protoplasm, nervous tissue, and bones
- Part of DNA material and energy distribution

Plants
- An essential plant macro-nutrient
- Formation of sugars and starches and conversion of solar energy into chemical energy

- Stimulation of early growth and root formation, and promotes plant hardiness and seed production
Good for ROOT Growth of both Plants & Human Hair
AGRONOMIC IMPACTS

ENVI RONMENTAL IMPACTS

Biosolids

USEPA (1986) Guideline for Agricultural Runoff P < 1 mg/L

Crop Uptake

Leaching

Runoff
Rainfall Simulation Study

Objective: To compare potential P losses from Class-A & Class-B biosolids when surface applied or mixed (incorporated) with soil.

- $H \rightarrow$ No difference in Class-A and Class-B biosolids.
- $H \rightarrow$ Mixing of biosolids will reduce P losses as compared with surface application.
Treatments

• Rates of Application
  – To meet crop N requirement (N basis)
  – To meet crop P requirement (P basis)

• Method of Application
  – Surface (S)
  – Incorporated (In)

• TSP rates – (Incorporated in soil)
  – Biosolids equivalent P based on N
  – Biosolids equivalent P based on P

• Control
Runoff Simulation

- National P Project Protocol – SERA 17
- Rainfall Simulator – Joern’s Inc.
- Eleven soils (3 Reps)
- Rainfall on Days 1, 3, and 7
- Rainfall – 7.0 cm/hr, 30-min runoff
- Runoff P analyses
  - Dissolved Molybdate Reactive P (DMRP) – 0.45µm filter
  - Total Dissolved P – 0.45µm filter, acid digest
  - Total P – unfiltered, acid digest
### DMRP in Runoff

<table>
<thead>
<tr>
<th>Treatments</th>
<th>P lost during 3 runs (mg/tray)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
</tr>
<tr>
<td><strong>N-Based</strong></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>9.1</td>
</tr>
<tr>
<td>Class B</td>
<td>5.6</td>
</tr>
<tr>
<td>TSP</td>
<td></td>
</tr>
<tr>
<td><strong>P-Based</strong></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>1.4</td>
</tr>
<tr>
<td>Class B</td>
<td>1.9</td>
</tr>
<tr>
<td>TSP</td>
<td></td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Particulate P in Runoff

<table>
<thead>
<tr>
<th>Treatments</th>
<th>P lost during 3 runs (mg/tray)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
</tr>
<tr>
<td><strong>N-Based</strong></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>27.9</td>
</tr>
<tr>
<td>Class B</td>
<td>128.5</td>
</tr>
<tr>
<td>TSP</td>
<td></td>
</tr>
<tr>
<td><strong>P-Based</strong></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>7.9</td>
</tr>
<tr>
<td>Class B</td>
<td>23.4</td>
</tr>
<tr>
<td>TSP</td>
<td></td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Total P in Runoff

<table>
<thead>
<tr>
<th>Treatments</th>
<th>P lost during 3 runs (mg/tray)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
<td>Incorporated</td>
<td></td>
</tr>
<tr>
<td><strong>N-Based</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>39.5</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Class B</td>
<td>137.2</td>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>TSP</td>
<td></td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td><strong>P-Based</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class A</td>
<td>11.2</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>Class B</td>
<td>29.7</td>
<td>18.7</td>
<td></td>
</tr>
<tr>
<td>TSP</td>
<td></td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td></td>
<td>8.7</td>
<td></td>
</tr>
</tbody>
</table>
Cake and Air-dried biosolids are different
Summary

• Greater losses of dissolved P occurred from surface applied Class-A biosolids, however total P losses were higher from class-B biosolids.

• Incorporating biosolids reduced the P losses substantially. Biosolids incorporation within 24 hrs of spreading is the best management practice followed in District’s farmland application program.

• Most of the losses were due to particulate P, so controlling erosion may reduce P losses substantially.
Objective: To compare the length of vegetative buffer strip for reducing particulate P losses from biosolids applied fields.

• H : Longer the buffer strip, less will be particulate P losses.
Treatments

P Sources = 2

Biosolids-Cake: (10dt/ac) = 210 lbs P/ac

TSP: Crop requirement

Vegetative Buffer = 3

0 ft
25 ft
50 ft

Replications = 3

0 ft
25 ft
50 ft
All the Fun at Fulton County:
Thanks Rosalie and FC staff

Bring Albert for some hard work next time.
Buffer Length and Particulate P

![Graph](image)

- **TSP**
  - 25 ft
  - 50 ft

- **Biosolids**
  - 25 ft
  - 50 ft
Summary

- We cannot reduce the P in agricultural runoff to ZERO, no matter what is the length of vegetative buffer strip.
- 25 ft buffer length was sufficient to reduce particulate P concentration to < 1 mg/L in 9 out of 10 runoff generating storm events.
- 50 ft is a good conservative length, the suggested length by IEPA for proposed regulation is 100 ft.
Fine-earth fraction
The Three Soil Separates

- Sand - 2.0 - 0.05 mm
- Silt – 50 – 2 um
- Clay - < 2 um

Time to Settle in Water Column
Sand = Secs
Silt = mins
Clay and Colloidal material = hrs
Cake and Air-dried biosolids behave differently

10 mins  30 mins  5 hrs  24 hrs
Imminent P-based Biosolids Land Application Rule

Is the District’s Farmland Application Program at Risk? No

- Selection of fields based on soil test and erosion potential
- Most of the losses were due to particulate P, so controlling erosion may reduce P losses substantially.
- BMP’s (e.g. vegetative buffers, WT-Residual Strips) in sensitive areas
Questions?

All biosolids are created equal but some are more Equal than others.

District Biosolids are ‘Celebrity Biosolids’