U.S. Agricultural Phosphorus Partial Nutrient Balances and Temporal Nutrient Use
Trends within Minnesota

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Abstract

The intensity of phosphorus use in United States food production systems has raised concerns about the use-efficiency of this non-renewable resource. Past research modeling the material flows of phosphorus has found that approximately one quarter of all phosphorus losses occur within the crop cultivation phase of phosphorus’s life cycle. Imbalanced phosphorus inputs and output can result in accumulations of phosphorus within the soil environment and possible phosphorus flows out of cropland. Improvements in phosphorus management are important because excess phosphorus input into the environment can drive hypoxia and cause eutrophication in freshwater, marine, and estuary aquatic ecosystems. The research being conducted in this study builds upon previous material flow analysis (MFA) research and quantifies the partial nutrient balance of phosphorus. Research conducted in this study uses nutrient use efficiency metrics to quantify the ratio of nutrient applied and crop biomass removal. Calculations of phosphorus partial nutrient balances measure system nutrient use sustainability, specifically by calculating the ratio of biomass removal to nutrient input application. Partial nutrient balances were calculated for 1997 within 48 states and within 84 Minnesota counties in 1987, 1992, and 1997. Research conducted in this study has found that phosphorus inputs at the state and county level exceed annual crop harvest, except for a few instances when nutrient removal exceeds inputs. The temporal analysis of partial nutrient balance change has determined that the balance of phosphorus removal and input has improved from 1987 to 1997. These results show that soil fertility, crop uptake, and nutrient application vary and agricultural land management may be improved to better balance crop removal with nutrient inputs.
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1. Introduction

Phosphorus is a critical element, essential for cell growth, and is being heavily utilized and relied upon to maintain productive agricultural systems. Phosphorus is commonly used in agricultural practice to balance nutrient removal that occurs during annual crop harvest. Growing world food demand means that efficient use of this resource is necessary to protect current agricultural practices and ensure future food security (Fixen, 2009; Cordell et al., 2009). Along with use-efficiency, nutrient use effectiveness is necessary to maintain adequate agricultural production levels and crop yields (Fixen, 2009). Nutrient use effectiveness can help ensure that nutrient inputs have the desired effect on agricultural productivity. Combined efforts to ensure agricultural nutrient effectiveness and efficiency will aid in efforts to maintain global food production, prevent potential unintentional off-field losses to the environment, and preserve non-renewable phosphorus resources for future generations.

1.1. Role of Phosphorus in Agricultural and the Environment

Physically phosphorus originates within the environment and serves as a major constituent of deoxyribonucleic acid (DNA) and adenosine triphosphate (ATP) (Karl et al., 2007; Mills et al., 2004). DNA and ATP are fundamental to inter/intra-cellular biological processes. Intra-cellular access and use of phosphorus is crucial in ensuring overall agricultural growth and productivity. In addition to cellular functions, phosphorus plays a role in altering inert nitrogen gas into a more biologically available form of nitrogen. Phosphorus can mobilize nitrogen through increases in the abundance
of nitrogen-fixing cyanobacteria associated with eutrophication (Schindler et al., 2008). Phosphorus’s role in increasing the mobilization of nitrogen has led to increased environmental concerns over eutrophication and water quality impacts. The dual role phosphorus plays in initiating environmental damage and maintaining agricultural productivity means that maximizing its use efficiency is crucial to ensure future environmental health and productive agricultural systems (Tilman et al., 2001; Tilman, 1999, Cordell et al., 2009).

Despite evidence supporting environmental damage associated with phosphorus, land managers historically have applied a surplus of phosphorus input without considering soil phosphorus supply, manure input, or crop specific requirements (Withers et al., 2005; Tilman, 1999; Smil, 2000). Improved evidence and data describing the balance of phosphorus input and removal will aid land managers who may lack precise information about phosphorus uptake (Withers et al., 2005; Waskom and Bauer, n.d.). Additionally, measurements of the balance between phosphorus input and removal can provide a uniform metric for comparing agricultural fertilizer uptake across agricultural regions. Comparisons, made possible by establishing phosphorus balances, are also important because they can function as indicators of agricultural performance (Snyder and Bruuslema, 2007).

Phosphorus is a key component in modern nutrient fertilizers. Typical phosphorus availability within fertilizer can vary from between 3 and 48 percent of the total mass of fertilizer applied (Busman et al., 2002; Smil, 2000). Some of the major fertilizers containing phosphorus include: superphosphate, concentrated superphosphate, monoammonium phosphate, diammonium phosphate, ammonium polyphosphate, and
rock phosphate (Rehm et al., 2010). Phosphorus that is used in fertilizer is mined from the earth as phosphate rock and converted into a more usable product (Suh and Yee, 2011). The majority of agricultural lands containing corn, wheat, barley, oats, peanuts, sorghum, soybeans, and rice undergo regular applications of phosphorus containing fertilizer (USGS, 2011; USDA, 2008; USDA, 2007 USDA, 2006; USDA, 2005; USDA, 2004). About one third of global land based ecosystems are under agricultural production, while in the United States, agricultural production occupies more than half of the total land mass (Tilman et al., 2001; Lubowski et al, 2006). The shear area of land under agricultural production and receiving supplemental nutrient input represents a massive demand for phosphorus fertilizer. Globally, phosphorus application rates, on preexisting agricultural land, has been steadily rising in conjunction with increases in global GDP and population (Tilman et al., 2001; Smil, 2000). The significant mass of phosphorus being applied to U.S. agricultural land is important because phosphorus flows and accumulation out of cropland are connected with damage to natural systems (Tilman et al., 2001; Tilman, 1999; Smil, 2000; Sharpley and Withers, 1994).

1.2. The Phosphorus Cycle

Phosphorus in the natural world does not exist in its elementary state, but instead exists in combination with other elements, as phosphate (Cordell et al., 2009; OECD, 2007). Phosphate is the combination of a phosphorus atom and multiple oxygen atoms. In the terrestrial environment phosphorus can be found as a mineral or as organic material such as soil humus or decomposing plant material (Smil, 2001; OECD, 2007). The phosphorus cycle is typically a closed loop and involves mobilization of soil phosphorus
by microbes, plant growth and uptake of phosphorus, followed by plant decomposition and phosphorus’s return to the soil (Smil, 2000; OECD, 2007). On agricultural lands the cyclical flow of nutrients is interrupted by both crop harvest and soil erosion (OECD, 2007). Without the addition of phosphorus, agricultural soil will experience decreased soil fertility and crop yields (Sharpley and Withers, 1994; OECD, 2007). Interruption and removal of phosphorus within the cycle necessitates the input of additional phosphorus through organic material or inorganic fertilizer (Sharpley and Withers, 1994; OECD, 2007). This interruption of the natural phosphorus cycle is important because it compels agricultural land managers to restore the soil phosphorus balance through the input of fertilizer.

Soil has an important role within the phosphorus cycle because it serves as both a source for phosphorus uptake by plants and a sink for phosphorus accumulation (Fixen et al., 2010; OECD, 2007). Phosphorus can enter and leave the agricultural system through numerous pathways (ANSI/ISO, 1007; Sharpley and Withers, 1994). Soil plays a unique role because it serves as a source for phosphorus flows in and out of the agricultural system. In modern agricultural systems, it is unlikely that phosphorus inputs are equivalent to phosphorus output, therefore agricultural soils will accumulate surplus phosphorus (Fixen, 2009; Sharpley, 1995). Sharpley (1995) generalized that approximately 67 percent of the annual phosphorus input remains in the agricultural system as surplus (Sharpley, 1995). Additionally, phosphorus accumulations within the soil can be so drastic that soil is unable to absorb any further phosphorus additions (Sharpley, 1995). These trends are important, but not indicative of the entire relationship between various forms of phosphorus and agricultural productivity.
1.3. Agricultural Phosphorus Management

Improved management of phosphorus is important for both environmental and economic reasons. Over-application, under application, and/or limited plant uptake of applied phosphorus represents a mismanagement of this critical resource. Phosphorus is applied to supplement nutrient deficiencies in the soil and phosphorus that does not get up taken by agricultural plants can flow out of agricultural system or become immobile within the agricultural system (Tilman et al., 2002; Busman et al., 2002). Additionally, phosphorus that does not directly aid in increasing soil fertility or crop production is of concern because it represents unintended economic losses and non-renewable resource misuse.

Previous studies have manipulated farm management input levels to determine their effects on agricultural productivity. The input and farm-level management practice changes include nutrient input levels, capital investment levels, yield, and crop prices (Tozer, 2009; Smil, 2000). Tozer (2009) found that reducing agricultural input levels and utilizing improved technologies, associated with better agriculture management, will result in greater crop productivity than without any management improvements (Bundy and Sturgul, 2001; Tozer, 2009). In some cases the impact of increased time, energy, and technology may outweigh physical reductions such as fertilizer and water (Bundy and Sturgul, 2001; Tozer, 2009). Agricultural management improvements often involve the use of improved technologies and capital equipment investment. Specific reductions in supplemental nutrient input can be achieved because of more accurate application and an improved balance between biomass output and nutrient input (Tozer, 2009). For
environmental reasons, reductions in the phosphorus input quantity and concentration of
soil phosphorus are important because the concentration of soil phosphorus is strongly
correlated to the quantity of dissolved phosphorus contained in agricultural runoff (Sims
and Vadas, 2005; Smil, 2000).

1.4. Phosphorus Use-Efficiency of Agriculture and Food System in the
U.S.

Previous research, in the field of phosphorus use, has found that approximately 24
% of United States phosphorus losses, destined for food production, occur within the
agricultural land stage of phosphorus’s life-cycle; therefore an increased understanding of
agricultural phosphorus use trends may help identify specific sectors in which efficiency
improvements can be achieved (Suh and Yee, 2011). The large share of phosphorus lost
is important to this study because it represents the second largest loss pathway and in-
field phosphorus losses are particularly vulnerable to run-off and difficult to recover (Suh
and Yee, 2011; Tilman et al., 2001). A 24 % loss of phosphorus input is important and
represents approximately 1000 kilotons of phosphorus that is unintentionally lost from
the domestic food production system (Suh and Yee, 2011). This massive loss of
phosphorus is important because it represents excess phosphorus, applied as fertilizer or
manure, which flows out of the agricultural system and may accumulate or flow into the
environment.

Quantifying the imbalance between inputs and outputs of agricultural phosphorus
can aid in efforts to reduce the negative impact of phosphorus on the environment
(Sharpley, 1995). In addition to quantifying use efficiency, determination of the
relationship between phosphorus input and crop output can help improve use efficiency (Cornia, 1984; Fixen, 2009). Agricultural inputs cannot exactly match outputs, but an improved understanding of phosphorus balances can help guide improvements in agricultural land management. Knowledge regarding net changes in phosphorus input and removal balances can aid in providing a solid science-based foundation in current nutrient use trends and environmental exposure to phosphorus (Fixen, 2009).

1.5. Major concerns related to phosphorus use

1.5.1 Environmental concerns

Mismanagement of phosphorus is of concern because phosphorus flows into the environment can promote eutrophication and terrestrial damage (Tilman et al., 2002; Tilman, 1999; Smil, 2000; Sharpley and Withers, 1994). Recent research has found that the limiting nutrient controlling eutrophication is phosphorus (Schindler et al., 2008). Schindler et al. (2008) found that when separately limiting both nitrogen and phosphorus, phosphorus was the limiting element in biomass growth associated with eutrophication. In other words, the reduction of nitrogen input into a watershed has little effect on eutrophication, but reducing phosphorus can reduce eutrophication (Schindler et al., 2008). One such study fertilized a lake with phosphorus and nitrogen and discovered that when nitrogen fertilization ceased, eutrophication would continue because of the increased abundance of nitrogen-fixing cyanobacteria (Schindler et al., 2008). This study also found that algal blooms, associated with eutrophication, were directly proportional to phosphorus inputs (Schindler et al., 2008). Therefore improved management of
phosphorus flows into the aquatic environment may help alleviate problems associated with phosphorus-nitrogen interactions.

Previous research analyzing flows of phosphorus within the U.S. food system has found that approximately 8% of total phosphorus lost from cropland enters waterways through runoff (Suh and Yee, 2011). An additional 16% of phosphorus is lost to agricultural soils and may be vulnerable to future flows, accumulation into aquatic environments, and accumulation in biomass (Suh and Yee, 2011). These losses indicate that phosphorus is being transported off of agricultural fields and is vulnerable for transport between agricultural, terrestrial, and aquatic ecosystems. Increased agricultural production demand means that our reliance on nutrient inputs will continue into the foreseeable future; therefore minimizing losses and damage associated with phosphorus is crucial.

1.5.2 Production concerns

In the context of resource conservation, the precise management of phosphorus is important because phosphorus must originate in mineral form and cannot be converted from any natural source other than rock phosphate. Additionally, phosphorus that is accessible and available to mobilize is finite and is not renewable in the foreseeable future (Cordell et al., 2009; Smil, 2000). Complicating the concern over a limited global phosphorus reserves is the fact that most of the significant phosphate rock reserves are only found in a small number of countries (Cordell et al., 2009). The limited geopolitical availability of phosphorus means that future phosphorus scarcity may be a global resource problem. Specifically, increases in the demand for phosphorus and a limited
geopolitical supply may eventually impact the international phosphorus supply chain and increase the importance of resource conservation.

1.5.3 Economic concerns

Inputs of phosphorus onto agricultural fields is of economic concern because excess phosphorus can have adverse effects on parties that benefit directly from agricultural production and on third parties who are impacted by environmental consequences of agricultural nutrient mismanagement. Phosphorous use is associated with damage to ecosystem services, demand caused increases in fertilizer costs, and declines in agricultural profitability (Tillman, 2002; Fixen, 2007). The improved crop productivity induced by supplemental phosphorus use is important for many reasons, but incidental economic damage must be restricted.

Ecosystem services are services provided by natural systems that provide a range of benefits to humans (Tilman et al., 2002). In the context of agriculture nutrient use, ecosystems services are important because they can be negatively impacted by improper agricultural resource management. Specifically, excess nutrient application and flows into surface water can result in higher water purification costs, damage fishing and recreational resources, and can reduce overall biodiversity (Tilman et al., 2002). Impacts to these three aquatic ecosystem services are important because restoration or substitution of the benefits necessitate economic adjustments. The negative economic impacts imposed on ecosystem services by improper fertilizer use clearly indicate why agricultural nutrient management is important.

The costs associated with excess fertilizer are also associated with the direct costs faced by agricultural land managers. Phosphorus that is purchased, applied, and lost from
agricultural fields represent inefficient use of economic resources. Excess and unused quantities of fertilizer input decrease agricultural land manager’s marginal returns on their fertilizer investments. Another reason why efficient use of agricultural nutrients is important is because demand and price are directly correlated (Fixen, 2006; Smil, 2000). Therefore agricultural production will be more expensive and overall costs per unit of fertilizer will continue to rise if the output per unit of nutrient input remains low. The economic costs of inefficient phosphorus use directly relate to the economic efficiency of using supplemental agricultural nutrients.

1.6. Prior nutrient use-efficiency research

Prior research, conducted by this author, in the field of phosphorus use efficiency has attempted to calculate regional crop-level use efficiency, based on phosphorus flows in an out of an acre unit of agricultural land. This research calculated phosphorus use efficiency using fertilizer, manure, soil phosphorus, and biomass harvest. Previous analysis of phosphorus use efficiency has shown that phosphorus inputs into agricultural land are exceeding biomass output. The exact magnitude of the imbalance between nutrient inputs and output ranges drastically by crop and by geographical region. These statistics are an important reference, but data limitations restrict the conclusions that are able to be made with this previous research. Specifically, the input data that was used in this author’s previous study was not completely representative of real world conditions. Multiple assumptions were used to convert each of the three inputs into a uniform metric. The previous analysis conducted does indicate that inputs and output are not balanced, but further analysis with more complete data is being conducted in this study. Use of
more refined data and a uniformed analysis metric will help to validate and strengthen the findings of this study.

1.7. Objectives, purpose, and hypothesis

The objectives of this study are to establish national and Minnesota phosphorus balance trends on agricultural land. Specifically, one objective is to establish phosphorus balance trends at the national level through the use of state-level phosphorus input/output data. An additional objective is to analyze phosphorus balances at the state level to establish historical phosphorus use trends in the context of Minnesota. By analyzing phosphorus balances this study will analyze the relationship between phosphorus inputs and biomass removal within the agricultural environment.

Accomplishing these objectives will help provide a scientific foundation relating to national and temporal phosphorus use trends. Phosphorus that is not removed through biomass removal is important because it may accumulate within agricultural soils and flow out of agricultural land. The purpose of the national level analysis is to develop a broad snapshot of recent nutrient use characteristics and removal efficiency patterns. The purpose of the state-level research is to gain greater geographic and temporal detail by measuring use efficiency over a time-span and in a more localized geographic area. This specific analysis aims to quantify how nutrient use practices have changed historically within Minnesota, by analyzing whether phosphorus is accumulating in soils or being “mined” from agricultural lands at three points of time in Minnesota. These two research objectives aim to analyze recent phosphorus use and historical use patterns in order to provide an index of agricultural sustainability.
National and state-level analysis aims to quantify how phosphorus is being used during agricultural practices. Previous research has found that phosphorus removed through biomass harvest does not match annual fertilizer input (Suh and Yee, 2011). Suh and Yee (2011) found that the phosphorus removed during annual crop harvest is less than annual input values and waste flows of phosphorus are substantial. This study hypothesizes that on a national level there will be a net increase in phosphorus accumulation and that agricultural phosphorus will not be balanced. The state-level analysis being carried out in this study is evaluating temporal changes in phosphorus. This study is specifically looking at phosphorus balance changes in both the short and long term. This study hypothesizes that within Minnesota phosphorus removal and input will not be balanced, but nutrient balances will improve between 1987 and 1997. Nutrient balances will likely improve because land management practices have improved the soil structure along with agricultural productivity.

2. Methods, data, and analytical framework

2.1. Analytical framework

2.1.1 Material flow analysis, industrial ecology, and material use efficiency (MFA/IE)

Previous studies in the field of industrial ecology have utilized the materials balance principal as a tool for developing indicators of environmental efficiency, eco-efficiency, and material cycling efficiency (Hashimoto and Moriguchi, 2004; Hoang and Rao, 2010; Zhang et al., 2008). Studies in material balances are rooted in the industrial
ecology tool of material flow analysis (MFA), which is designed to measure physical resource flows in and out of a defined system (Brunner and Rechberger, 2003).

Numerous indicators have been proposed to track the material stocks and flows through anthropogenic and environmental use networks. For instance, Hashimoto and Morigushi (2004) proposed six indicators of material cycles to describe society’s natural metabolism (Hashimoto and Moriguchi, 2004). Indicators of material cycles are a valuable tool to objectively measure the effectiveness of specific management practices or policies.

One indicator used to analyze material cycles proposed by Hashimoto and Moriguchi (2004), material use efficiency (MUE), is defined as a fraction of the material utilized versus the amount of material consumed. The fraction generated is an indicator of the effectiveness or efficiency of a process and indicates what percent of the input is utilized to produce the desired functional output (Hashimoto and Moriguchi, 2004). Essentially, this fraction is being used in this study to measure how much phosphorus entering the agricultural system exits the system as usable biomass. The calculated values of MUE correspond directly to use efficiency, therefore a fraction value closer to 1(100%) will have a higher use efficiency than a value closer to 0(0%).

Theoretical studies involving the use of the mass balance have defined pollution as the difference between nutrient output and nutrient input (Hoang and Rao, 2010). This simplified approach utilizes the law of mass conservation and is based on a single variable production input (Hoang and Rao, 2010; Hashimoto and Morigushi, 2004). Often times the objective of these types of analysis is to minimize the quantity of ‘bad’ output (Hoang and Rao, 2010). Operating within the mass balance framework, a decrease in the quantity of ‘bad’ output may coincide with a decrease in input or a
possible increase in ‘good’ output. Theoretical mass balance theory is being applied in an agricultural context to quantify the balance of phosphorus input and removal within agricultural lands of the United States and Minnesota.

**2.1.2 Phosphorus-use efficiency framework**

Similar to industrial ecology principals, agricultural production ecology can be defined by the inputs and the outputs of agricultural production systems (Ittersum and Rabbinge, 1997). Principals founded in industrial ecology are shared by agronomic indices of sustainability, such as partial factor productivity, agronomic efficiency, partial nutrient balance, and recovery efficiency (Snyder and Bruulsema, 2007; Hashimoto and Morigushi, 2004). This study analyzes the balance of phosphorus using the soil surface balance, which means that inputs and outputs will be evaluated on the basis of agricultural system inputs and nutrient uptake (OECD, 2007). The input of phosphorus into the agricultural environment can be considered a non-substitutable input because it is necessary to fulfill a specific role in plant growth. Additional substitutable inputs, like labor, water, and mechanization are not being considered in the scope of this study. Inputs of phosphorus in this study are going to be expressed in physical units, specifically as kilograms of phosphorus input. Data presented in this study represents elemental phosphorus unless otherwise noted. The output in this study is representative of agricultural crops and is being measured by crop-level yield of biomass. Calculated output is being expressed in physical units, specifically as kilograms of removed phosphorus. Due to the scale and aggregation levels in this study, the role of the physical environment differences is not being factored into this analysis. This study assumes that
specific agricultural nutrient management practices will vary regionally, but will endeavor to quantify the balance between crop phosphorus uptake and phosphorus inputs.

This study’s analysis of the phosphorus balances on agricultural lands is going to utilize the **target oriented approach**. A target oriented approach suggests that inputs will be tailored by a known output level (Ittersum and Rabbinge, 1997). Utilization of the target oriented approach dictates a need for prior knowledge regarding input-output levels. Calculation of the current balance between inputs and outputs will provide valuable knowledge about the current agricultural phosphorus balance. Baseline knowledge about the current phosphorus balance will help guide future efforts to reduce or possibly increase the input of phosphorus and tailor inputs to biomass output.

Another important concept in assessing input-output relationships on farms is the idea of equilibrium, which can be defined as a stable system in which nutrient inputs and outputs are in balance (Ittersum and Rabbinge, 1997; Fixen, 2009). Quantification of phosphorus inputs and outputs will aid in contrasting how current agricultural systems differ from the conceptual balance suggested by the concept of agricultural equilibrium. The concept of theoretical agricultural nutrient equilibrium is useful to help measure the potential for input reductions. Evidence suggests that reduced phosphorus inputs, achieved through a target-oriented approach, will result in reduction of in-field phosphorus runoff (Sharpley et al., 2003).

Improving our understanding of phosphorus use efficiency is important to ensure future sustainable agricultural production, an adequate supply of phosphorus nutrients, and to reduce the negative environmental impact associated with phosphorus (Tilman, 2002). Measurement of the environmental impacts of resource use, such as phosphorus,
is defined as **resource efficiency** and measurement of just the environmental impacts of waste output is defined by **environmental efficiency** (Zhang et al. 2008). In the context of resource conservation, guided management of phosphorus is important because limited mineral sources of rock phosphate exist. Additionally, phosphorus that is recoverable and available to mobilize is finite and is not renewable in the foreseeable future (Cordell et al., 2009; Smil, 2000). Improved knowledge surrounding agricultural nutrient use patterns is fundamental in evaluating system sustainability and understanding nutrient input effectiveness.

Accurate measurement of agricultural nutrient use efficiency requires the use of performance indicators (Fixen, 2009; Snyder and Bruulsema, 2007). Performance indicators provide a consistent and uniform measure of agricultural system productivity. One indicator of how well phosphorus is recovered by cropping systems is **recovery efficiency**. Recovery efficiency is the ratio of the amount of nutrient recovered in aboveground biomass that has and has not received supplemental nutrient input (Bruulsema et al., 2004; Snyder and Bruuslema, 2007). Calculation of recovery efficiency is done by using control plots to measure increases in in crop uptake for every unit increase in nutrient application (Snyder and Bruulsema, 2007). Measurement of recovery efficiency is largely dependent on what part of the plant is being measured and which inputs (fertilizer, manure, soil, atmospheric deposition, etc.) to include. Control plots necessary to calculate recovery efficiency are not readily available, so this study used another indicator to determine phosphorus use efficiency, the **partial nutrient balance (PNB)**. Partial nutrient balance is calculated by dividing nutrient content of crop yield (Y) by the amount of nutrient applied (F) (Eqt. 1). Calculation of partial nutrient
balance allows for comparison between different cropping systems (Snyder and Bruulsema, 2007). In the context of this study, partial nutrient balance is evaluating current nutrient use patterns and temporal changes in nutrient use efficiency.

\[ PNP = \frac{Y}{F} \]

Figure 1. Partial nutrient balance equation

2.2 Data requirements and analysis

In order to analyze the use efficiency of phosphorus data is needed to quantify how much phosphorus is removed and applied to agricultural land. The data being drawn upon is being taken from government statistical databases representing the best available data. This data will be used to calculate how much phosphorus is removed in the harvested portion of agricultural crops in relation to how much nutrient applied through manure and fertilizer (Snyder and Bruulsema, 2007). Partial nutrient balances close to one represent ideal agricultural nutrient management because removal of the applied nutrients is close to equilibrium. Partial nutrient balances greater than one represent nutrient surpluses and values of less than one represent nutrient deficient agricultural systems (Snyder and Bruuslema, 2007).

2.2.1 National-level data and analysis

At the national level, phosphorus removal efficiency is going to be analyzed using the base year 1997, because it represents the most current and comprehensive data for fertilizer input, manure input, and biomass harvest. The fertilizer and manure input data that is being used is from the United States Geological Survey’s county level estimates
County level input figures have been aggregated to represent state nutrient input totals. Crop removal data has been gathered through custom queries in the USDA-NASS Quick Stats 2.0 statistical database (USDA-NASS, 2011a). Data queried from this database represent crop-specific state level crop harvest. In order to compare phosphorus input and crop removal, removal values are being converted to kilograms of phosphorus. This conversion is done by converting the surveyed weight to kilograms of phosphorus using USDA-NRCS Nutrient Content of Crop data to multiply the total mass reported by the percent of nutrient contained in that specific crop (USDA-NRCS, 2011)(eqt. 2). Data presented in this study represents elemental phosphorus unless otherwise noted. After converting the input and output data to represent kilograms of elemental phosphorus it is then used in the partial nutrient balance equation to determine phosphorus removal efficiency (eqt. 1).

\[
\text{Total Mass} (Kg) \times \text{Percent Nutrient} \left(\%\right) = \text{Kilograms of Phosphorus}
\]

**Equation 2. Conversion of crop removal mass to kilograms of elemental phosphorus nutrient removal**

### 2.2.2 State-level data and analysis

At the state level, phosphorus removal efficiency was analyzed at the county level for three years: 1987, 1992, and 1997. These three harvest years are being used because they represent the most comprehensive data for fertilizer input, manure input, and biomass harvest. The fertilizer and manure input data that is being used is from the United States Geological Survey’s county level estimates (Ruddy et al., 2006). Individual county level nutrient input figures are being used along with county-level crop removal data. County-level crop removal data have been gathered through custom queries in the USDA-NASS Quick Stats 2.0 statistical database (USDA-NASS, 2011).
Data queried from this database represents county level, crop-specific biomass harvest. In order to compare phosphorus input and crop removal, the crop removal data is converted to kilograms of phosphorus. This conversion is done by converting the surveyed weight to kilograms by using USDA-NRCS *Nutrient Content of Crop* data to multiply the total mass reported by the percent of nutrient contained in that specific crop (USDA-NRCS, 2011) (Eqt. 2). After converting the input and output data to represent kilograms of elemental phosphorus, it is then used in the partial nutrient balance equation to determine phosphorus removal efficiency (eqt. 1).

3. Results

The results of this study indicate that the quantity of nutrient applied to agricultural fields does not necessarily equal the amount of nutrient removed through annual crop harvest. Analysis of nutrient inputs and output has shown that nutrient application can be greater or less than the quantity of nutrients applied. The balance between nutrient inputs and removal varies widely geographically and temporally.

3.1. National Level

3.1.1 Phosphorus input/output values

At the national level, phosphorus balances based on nutrient input and removal has been calculated for 48 states. Phosphorus nutrient input is the combination of nutrients applied in the form of manure and fertilizer. Agricultural nutrient contribution from manure and fertilizer varies, but average fertilizer and manure contributions are 51% and 49%, respectively (Table. 1). Nutrient contributions, from fertilizer, within
individual states can vary from as low as 18% to as high as 83% (Table 1). Nutrient contributions from manure can range from as low as 17% to as high as 82% (Table 1).

Table 2 shows the mass of phosphorus applied for each state being analyzed in this study (Table 2). Regardless of the contribution percentage, the sum of manure and fertilizer input is representative of the total amount of phosphorus input to that state’s agricultural land. The total mass of both these forms of phosphorus is being used in the analysis to calculate partial nutrient balance.

<table>
<thead>
<tr>
<th>Nutrient Percent Contribution</th>
<th>Fertilizer</th>
<th>Manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>51%</td>
<td>49%</td>
</tr>
<tr>
<td>Min</td>
<td>18%</td>
<td>17%</td>
</tr>
<tr>
<td>Max</td>
<td>83%</td>
<td>82%</td>
</tr>
</tbody>
</table>

Table 1. National manure and fertilizer nutrient percent contributions
<table>
<thead>
<tr>
<th>State</th>
<th>Fertilizer</th>
<th>Manure</th>
<th>State</th>
<th>Fertilizer</th>
<th>Manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>2E+07</td>
<td>4E+07</td>
<td>Nebraska</td>
<td>8E+07</td>
<td>1E+08</td>
</tr>
<tr>
<td>Arizona</td>
<td>1E+07</td>
<td>1E+07</td>
<td>Nevada</td>
<td>2E+06</td>
<td>7E+06</td>
</tr>
<tr>
<td>Arkansas</td>
<td>4E+07</td>
<td>5E+07</td>
<td>New Ham</td>
<td>2E+05</td>
<td>5E+05</td>
</tr>
<tr>
<td>California</td>
<td>8E+07</td>
<td>7E+07</td>
<td>New Jer</td>
<td>5E+06</td>
<td>1E+06</td>
</tr>
<tr>
<td>Colorado</td>
<td>2E+07</td>
<td>4E+07</td>
<td>New Mex</td>
<td>5E+06</td>
<td>2E+07</td>
</tr>
<tr>
<td>Connecticut</td>
<td>6E+05</td>
<td>2E+06</td>
<td>New York</td>
<td>2E+07</td>
<td>2E+07</td>
</tr>
<tr>
<td>Delaware</td>
<td>3E+06</td>
<td>4E+06</td>
<td>North Can</td>
<td>5E+07</td>
<td>7E+07</td>
</tr>
<tr>
<td>Florida</td>
<td>3E+07</td>
<td>3E+07</td>
<td>North Dak</td>
<td>7E+07</td>
<td>3E+07</td>
</tr>
<tr>
<td>Georgia</td>
<td>6E+07</td>
<td>4E+07</td>
<td>Ohio</td>
<td>6E+07</td>
<td>3E+07</td>
</tr>
<tr>
<td>Idaho</td>
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<td>2E+07</td>
<td>Oklahoma</td>
<td>3E+07</td>
<td>8E+07</td>
</tr>
<tr>
<td>Illinois</td>
<td>2E+08</td>
<td>4E+07</td>
<td>Oregon</td>
<td>2E+07</td>
<td>2E+07</td>
</tr>
<tr>
<td>Indiana</td>
<td>8E+07</td>
<td>3E+07</td>
<td>Pennsylv</td>
<td>2E+07</td>
<td>3E+07</td>
</tr>
<tr>
<td>Iowa</td>
<td>1E+08</td>
<td>1E+08</td>
<td>Rhode Isla</td>
<td>2E+05</td>
<td>1E+05</td>
</tr>
<tr>
<td>Kansas</td>
<td>8E+07</td>
<td>8E+07</td>
<td>South Can</td>
<td>1E+07</td>
<td>1E+07</td>
</tr>
<tr>
<td>Kentucky</td>
<td>4E+07</td>
<td>4E+07</td>
<td>South Dak</td>
<td>5E+07</td>
<td>6E+07</td>
</tr>
<tr>
<td>Louisiana</td>
<td>2E+07</td>
<td>2E+07</td>
<td>Tennessee</td>
<td>4E+07</td>
<td>3E+07</td>
</tr>
<tr>
<td>Maine</td>
<td>2E+06</td>
<td>1E+06</td>
<td>Texas</td>
<td>9E+07</td>
<td>2E+08</td>
</tr>
<tr>
<td>Maryland</td>
<td>1E+07</td>
<td>9E+06</td>
<td>Utah</td>
<td>6E+06</td>
<td>1E+07</td>
</tr>
<tr>
<td>Massachus</td>
<td>2E+06</td>
<td>9E+05</td>
<td>Vermont</td>
<td>1E+06</td>
<td>3E+06</td>
</tr>
<tr>
<td>Michigan</td>
<td>4E+07</td>
<td>2E+07</td>
<td>Virginia</td>
<td>2E+07</td>
<td>3E+07</td>
</tr>
<tr>
<td>Minnesota</td>
<td>1E+08</td>
<td>6E+07</td>
<td>Washington</td>
<td>2E+07</td>
<td>2E+07</td>
</tr>
<tr>
<td>Mississipp</td>
<td>2E+07</td>
<td>3E+07</td>
<td>West Vir</td>
<td>4E+06</td>
<td>8E+06</td>
</tr>
<tr>
<td>Missouri</td>
<td>7E+07</td>
<td>8E+07</td>
<td>Wisconsin</td>
<td>5E+07</td>
<td>4E+07</td>
</tr>
<tr>
<td>Montana</td>
<td>3E+07</td>
<td>4E+07</td>
<td>Wyoming</td>
<td>1E+07</td>
<td>3E+07</td>
</tr>
</tbody>
</table>

Table 2. State Nutrient Inputs
Phosphorus percent content of major agricultural crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>Phosphorus percent</th>
<th>Crop</th>
<th>Phosphorus percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>0.35%</td>
<td>Peas</td>
<td>0.49%</td>
</tr>
<tr>
<td>Beans</td>
<td>0.54%</td>
<td>Rice</td>
<td>0.29%</td>
</tr>
<tr>
<td>Corn-Grain</td>
<td>0.31%</td>
<td>Rye</td>
<td>0.38%</td>
</tr>
<tr>
<td>Corn-Silage</td>
<td>0.38%</td>
<td>Sorghum - grain</td>
<td>0.33%</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.41%</td>
<td>Sorghum - silage</td>
<td>0.21%</td>
</tr>
<tr>
<td>Flaxseed</td>
<td>0.57%</td>
<td>Soybeans</td>
<td>0.67%</td>
</tr>
<tr>
<td>Forage</td>
<td>0.26%</td>
<td>Sugarbeets</td>
<td>0.24%</td>
</tr>
<tr>
<td>Forage - Hay</td>
<td>0.22%</td>
<td>Sugarcane</td>
<td>0.24%</td>
</tr>
<tr>
<td>Lentils</td>
<td>0.43%</td>
<td>Sunflower</td>
<td>0.62%</td>
</tr>
<tr>
<td>Oats</td>
<td>0.38%</td>
<td>Tobacco</td>
<td>0.31%</td>
</tr>
<tr>
<td>Peanuts</td>
<td>0.35%</td>
<td>Wheat</td>
<td>0.42%</td>
</tr>
</tbody>
</table>

USDA, NRCS, Crop nutrient results, http://plants.usda.gov/npk/main

Table 3. Phosphorus percent content of major agricultural crops

Phosphorus that is removed through crop harvest has been determined with surveyed harvest statistics of 22 major field crops. Not every crop is grown in each state but the primary agricultural field crops include: barley, beans, corn-grain, corn-silage, cotton, flaxseed, forage, forage-hay, lentils, oats, peanuts, peas, rice, rye, sorghum-grain, sorghum-silage, soybeans, sugarbeets, sugarcane, sunflower, tobacco, and wheat. The average phosphorus content is listed in table 3 and differs for every major crop (Table 3.). Listed on table 3 are the phosphorus content values for all 22 major crops.

Approximately 85% of phosphorus being removed from agricultural land is being removed through the harvest of corn-grain, corn-silage, forage, forage-hay, and soybeans (Table 4.).
Table 4. Average crop contribution and mass of phosphorus removal

<table>
<thead>
<tr>
<th>Crop</th>
<th>Percent</th>
<th>Mass (Kgs)</th>
<th>Crop</th>
<th>Percent</th>
<th>Mass (Kgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>1.8%</td>
<td>2.77E+07</td>
<td>Peas</td>
<td>0.1%</td>
<td>9.19E+05</td>
</tr>
<tr>
<td>Beans</td>
<td>0.3%</td>
<td>7.19E+06</td>
<td>Rice</td>
<td>1.1%</td>
<td>2.38E+07</td>
</tr>
<tr>
<td>Corn-Grain</td>
<td>17.8%</td>
<td>7.20E+08</td>
<td>Rye</td>
<td>0.1%</td>
<td>7.72E+05</td>
</tr>
<tr>
<td>Corn-Silage</td>
<td>24.9%</td>
<td>3.34E+08</td>
<td>Sorghum - grain</td>
<td>1.5%</td>
<td>5.28E+07</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.4%</td>
<td>1.75E+07</td>
<td>Sorghum - silage</td>
<td>0.4%</td>
<td>1.03E+07</td>
</tr>
<tr>
<td>Flaxseed</td>
<td>0.0%</td>
<td>3.32E+05</td>
<td>Soybeans</td>
<td>13.1%</td>
<td>4.52E+08</td>
</tr>
<tr>
<td>Forage</td>
<td>10.4%</td>
<td>1.87E+08</td>
<td>Sugarbeets</td>
<td>2.5%</td>
<td>6.61E+07</td>
</tr>
<tr>
<td>Forage - Hay</td>
<td>19.5%</td>
<td>3.01E+08</td>
<td>Sugarcane</td>
<td>3.1%</td>
<td>6.12E+07</td>
</tr>
<tr>
<td>Lentils</td>
<td>0.0%</td>
<td>2.18E+05</td>
<td>Sunflower</td>
<td>0.3%</td>
<td>1.01E+07</td>
</tr>
<tr>
<td>Oats</td>
<td>0.4%</td>
<td>8.94E+06</td>
<td>Tobacco</td>
<td>0.3%</td>
<td>2.53E+06</td>
</tr>
<tr>
<td>Peanuts</td>
<td>0.6%</td>
<td>5.62E+06</td>
<td>Wheat</td>
<td>0.2%</td>
<td>4.57E+06</td>
</tr>
</tbody>
</table>

Table 4. Average crop contribution and mass of phosphorus removal

3.1.2 National level partial nutrient balance calculation

By utilizing the nutrient content data (Table 3) and crop removal data, partial nutrient balances are able to be calculated for individual states for the year 1997. Partial nutrient balance calculations greater than 1 indicate a nutrient input surplus and values less than 1 indicate nutrient input deficiency (Snyder and Bruulsema, 2007). Individual state’s partial nutrient balances are displayed in table 5 and range significantly between the 48 states being analyzed (Table 5.). The average partial nutrient balance was 0.66, the highest is 1.79, and the lowest is 0.16 (Table 6.). The extreme range of the average, high, and low values indicate that trends in agricultural nutrient management vary widely amongst the states analyzed.
Table 5. Partial nutrient balances values for 48 states

<table>
<thead>
<tr>
<th>State</th>
<th>PNB</th>
<th>State</th>
<th>PNB</th>
<th>State</th>
<th>PNB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>0.17</td>
<td>Maine</td>
<td>0.61</td>
<td>Ohio</td>
<td>1.09</td>
</tr>
<tr>
<td>Arizona</td>
<td>0.42</td>
<td>Maryland</td>
<td>0.47</td>
<td>Oklahoma</td>
<td>0.20</td>
</tr>
<tr>
<td>Arkansas</td>
<td>0.42</td>
<td>Massachusetts</td>
<td>0.78</td>
<td>Oregon</td>
<td>0.37</td>
</tr>
<tr>
<td>California</td>
<td>0.54</td>
<td>Michigan</td>
<td>1.16</td>
<td>Pennsylvania</td>
<td>0.92</td>
</tr>
<tr>
<td>Colorado</td>
<td>0.66</td>
<td>Minnesota</td>
<td>1.04</td>
<td>Rhode Island</td>
<td>0.79</td>
</tr>
<tr>
<td>Connecticut</td>
<td>1.17</td>
<td>Mississippi</td>
<td>0.49</td>
<td>South Carolina</td>
<td>0.28</td>
</tr>
<tr>
<td>Delaware</td>
<td>0.43</td>
<td>Missouri</td>
<td>0.53</td>
<td>South Dakota</td>
<td>0.88</td>
</tr>
<tr>
<td>Florida</td>
<td>0.62</td>
<td>Montana</td>
<td>0.43</td>
<td>Tennessee</td>
<td>0.32</td>
</tr>
<tr>
<td>Georgia</td>
<td>0.16</td>
<td>Nebraska</td>
<td>0.87</td>
<td>Texas</td>
<td>0.28</td>
</tr>
<tr>
<td>Idaho</td>
<td>0.80</td>
<td>Nevada</td>
<td>0.60</td>
<td>Utah</td>
<td>0.74</td>
</tr>
<tr>
<td>Illinois</td>
<td>0.96</td>
<td>New Hampshire</td>
<td>1.79</td>
<td>Vermont</td>
<td>1.58</td>
</tr>
<tr>
<td>Indiana</td>
<td>0.97</td>
<td>New Jersey</td>
<td>0.61</td>
<td>Virginia</td>
<td>0.33</td>
</tr>
<tr>
<td>Iowa</td>
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<td>New Mexico</td>
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<td>Washington</td>
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</tr>
<tr>
<td>Kansas</td>
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<td>1.43</td>
<td>West Virginia</td>
<td>0.35</td>
</tr>
<tr>
<td>Kentucky</td>
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<td>North Carolina</td>
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<td>Wisconsin</td>
<td>1.15</td>
</tr>
<tr>
<td>Louisiana</td>
<td>1.17</td>
<td>North Dakota</td>
<td>0.56</td>
<td>Wyoming</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 5. Partial nutrient balances values for 48 states

Figure 1. PNB balance of 48 U.S. States
3.1.3 State-level phosphorus removal efficiency

Analysis of just the average and range of PNB/removal efficiency is important, but does not provide detailed information about which states have a nutrient surplus and which have a nutrient deficiency. The PNB values for the 48 analyzed states have been graphically displayed with a histogram and a color coded map (Figure 1, 2). The vertical axis on this histogram represents the number of states and the horizontal axis represents a particular range of PNB values. The majority of state partial nutrient balances lie between 0.43 and 1.24 (Figure 1, 2). The proximity to one, distribution, and frequency of data is important because it is a useful indicator of agricultural system sustainability. Figure(s) 1 and 2 illustrate how the majority of states have PNBs below one and therefore are nutrient deficient.

Table 6. State-level average, low, and high partial nutrient balances

<table>
<thead>
<tr>
<th>PNB</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.66</td>
</tr>
<tr>
<td>High</td>
<td>1.79</td>
</tr>
<tr>
<td>Low</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Partial nutrient balance of agricultural phosphorus use
3.2. State Level

3.2.1 Phosphorus input/output values

The data and methodology used to calculate the agricultural partial nutrient balance within Minnesota are very similar to what has been done at the national level. The primary difference involved in this state-level analysis is that nutrient input and biomass removal is being calculated for each of the 84 Minnesota’s counties. Another difference is that PNBs are being calculated, in three years, over a ten year time span.

Phosphorus nutrient input is the combination of nutrients applied in the form of manure and fertilizer. During each time period average nutrient contributions vary, but nutrient contributions from fertilizer outweigh manure in each time period analyzed.
(Table 7.). During the three years evaluated nutrient contributions, from fertilizer, within individual counties can vary from as low as 16% to as high as 96% (Table 7).

Additionally, nutrient contributions from manure can range from 4% to 84% (Table 7).

Regardless how much phosphorus comes from either source, the sum of both sources has been used to calculate the amount of nutrient applied.

<table>
<thead>
<tr>
<th>Minnesota Nutrient Fertilizer Manure Percent Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer</td>
</tr>
<tr>
<td>%</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Max</td>
</tr>
<tr>
<td>Min</td>
</tr>
</tbody>
</table>

Table 7. Minnesota manure and fertilizer percent contributions in 1987, 1992, and 1997

Phosphorus that is removed from Minnesota’s agricultural land has been calculated using 11 major crops that are grown within Minnesota. The 11 crops used to calculate nutrient removal include: barley, beans, corn-grain, corn-silage, flaxseed, oats, peas, rye, soybeans, sunflower, and wheat. Not all of these 11 crops are grown in every Minnesota county, but every crop is grown at a substantial level within at least one Minnesota county. The values for average phosphorus content are identical as what has been used at the national level (Table 3). Conversion of annual county-level crop yields into phosphorus has shown that the majority of phosphorus is removed from agricultural land through the harvest of corn-grain, corn-silage, and soybeans (Table 8.)
Table 8. Phosphorus removal crop contributions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>8%</td>
<td>8%</td>
<td>4%</td>
</tr>
<tr>
<td>Beans</td>
<td>0%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Corn-Grain</td>
<td>36%</td>
<td>42%</td>
<td>40%</td>
</tr>
<tr>
<td>Corn-Silage</td>
<td>27%</td>
<td>24%</td>
<td>23%</td>
</tr>
<tr>
<td>Flaxseed</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Oats</td>
<td>7%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Peas</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Rye</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>21%</td>
<td>19%</td>
<td>26%</td>
</tr>
<tr>
<td>Sunflower</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>Wheat</td>
<td>0%</td>
<td>1%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 8. Phosphorus removal crop contributions

3.2.2 Temporal evaluation of county-level phosphorus partial nutrient balances

Analysis of county-level phosphorus partial nutrient balances show that variability exists between individual counties and years. Partial nutrient balances have been calculated for 3 years in 84 Minnesota counties (Table 9.). During 1987, 1992, 1997 Minnesota phosphorus partial nutrient balances range from as low as 0 up to 1.26 with average values of 0.76, 0.77, and 0.79. (Table 10). Between 1987 and 1997 the average state PNB improved from 0.76 to 0.79 (Table 10). Along with these general trends, the distribution of county PNBs can provide insight into how many counties fall close to a PNB value of 1 (Figure 3).
The distribution of individual county PNBs is an important indicator of agricultural system sustainability. County-level PNB distribution close to 1 indicate system sustainability, therefore having more counties close to one represents greater system sustainability. The PNBs of the majority of counties are in close proximity to 1, but it is clear that some counties have very low PNBs and many exceed 1 (Figure 3). A
slight improvement in PNB is noticeable from 1987 to 1997, this is evident when bars on
the histogram are clustered around 1 and because the average PNB has increased in the
ten year time span being analyzed (Figure 3), (Table 10). One important result of
comparing these three growing seasons is that a significant amount of counties have
phosphorus partial nutrient balances very close to 1. Additionally, it is important to note
that slight improvements in the balance between phosphorus inputs and removal have
occurred between 1987 and 1997.

![MN PNB distribution](image)

**Figure 3. Distribution of county-level phosphorus partial nutrient balances: 1992**

4. Discussion

This study’s findings illustrate that crop nutrient uptake output does not match
crop nutrient inputs. Analysis of both state-level and Minnesota county-level data has
shown that partial nutrient balances can be either in surplus or less than their respective nutrient removal value. This study’s findings indicate that the majority of phosphorus partial nutrient balances in states and Minnesota counties are below the optimum level of 1. Agricultural management has not been completely successful in balancing phosphorus inputs and output, thus improved knowledge of recent phosphorus balances will be helpful in minimizing sensitive source areas (Sharpley, 1995; Fixen, 2009). Partial nutrient balance values are a useful metric to evaluate the sustainability of agricultural management practices. Partial nutrient balance values close to one indicate an ideal management situation and minimal opportunities for in-field nutrient losses (Snyder and Bruulsema, 2007). Use of and proper management of agricultural nutrients is important to prevent environmental damage and ensure economically optimum agricultural production.

4.1. National partial nutrient balance implications

The partial nutrient balance of phosphorus, in 48 states, ranges from .69 to 1.79 with ten states exceeding 1 and thirty eight states below 1. This distribution of phosphorus indicates that the majority of agricultural systems are phosphorus deficient (Table 6). Although it is outside the bounds of this study to determine the eventual fate of unaccounted for nutrients, the fact that nutrient removal is below nutrient application indicates that phosphorus is going unaccounted for and losses to the environment are possible. Measurement of nutrient use efficiency is important because it can help guide agricultural land managers in nutrient input decisions and implementation of best management practices.
4.2. Minnesota partial nutrient balance implications

The partial nutrient balance of phosphorus, in 84 Minnesota counties, over 3 time periods ranges from 0 to 1.26 (Table 10). Similar to national level PNB, the majority of counties PNBs are below 1 (Table 10). In the years 1987, 1992, and 1997 no more than 13 counties had PNBs greater than 1; therefore nutrient use efficiency improvements are possible for the majority of Minnesota counties (Table 11). Efficiency improvements may involve improvements in crop yield, changes in the quantity of nutrient input, implementation of agricultural best management practices, or uncontrollable factors such as weather.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PNB &gt; 1</td>
<td>10</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>PNB &lt; 1</td>
<td>74</td>
<td>70</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 11. Partial nutrient balance distribution among 84 Minnesota counties in 1987, 1992, and 1997

Temporal changes in partial nutrient balance represent changes in nutrient management, yield improvements, and technological improvements. The overall percent change between 1987 and 1997 is 32%. The PNB percent change between 1987-1992 and 1992-1997 are 5% and 20%, respectively. Positive changes in partial nutrient balance in all three time periods indicates that nutrient inputs have decreased, soil fertility may have changed, nutrient removals have increased, or a combination of many factors (Snyder and Bruulsema, 2007). The distribution of county-level percent changes in PNB between 1987 and 1997 can be seen in figure 4. It is clear that reductions and improvements in phosphorus balances, between 1987 and 1997, have considerable spatial distribution within Minnesota (Figure 4). Spatial differences in PNB are so significant
that neighboring counties can exhibit the greatest gains and greatest losses in PNB (Figure 4). Overall increases in nutrient use efficiency are important because they represent overall improvements in agricultural nutrient use efficiency, system sustainability, or other potential impacts on agricultural growing conditions.

<table>
<thead>
<tr>
<th>PNB Percent change</th>
<th>87-92</th>
<th>92-97</th>
<th>87-97</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>5%</td>
<td>20%</td>
<td>33%</td>
</tr>
</tbody>
</table>

Figure 4. Minnesota county-level absolute PNB percent change between 1987-1997

4.3 Agricultural management improvement options

The results of this study have shown that phosphorus inputs are not in balance with phosphorus removed via crop harvest, therefore efforts in agricultural nutrient management may help improve this balance. Theoretical nutrient use efficiency in
agricultural plants is controlled by many factors including: soil properties, crop uptake efficiency, climate, chemical species of the fertilizer, and mychorizal interactions (Baligar et al., 2001; Smil, 2000). Better management of agricultural nutrients may help accomplish social, ecological, and economic objectives related to agricultural food production. Improved agricultural management techniques, also known as best management practices, can help modify existing agricultural practices to match agricultural objectives (Bruuslema et al., 2008; Fixen, 2009), (Figure 5). Implementation of best management practices are intended to satisfy four objectives of productivity, profitability, sustainability, and environmental protection (Figure 5).

Figure 5. Global framework for best management practices (BMPs) for fertilizer use (Bruuslema, 2008)

These four objectives are important in ensuring efficient use of phosphorus because they seek to maximize crop yields, increase agricultural land manager revenue, ensure future resource use efficiency, and protect overall environmental health.
Practices and factors that are specific to fertilizer management include: fertilizer specific BMPs, fertilizer source, fertilizer application rate, fertilizer application timing, and fertilizer placement (Bruuslema et al., 2008). Agricultural productivity can be influenced by many factors other than just nutrient input quantity; therefore reductions in any one input should be accompanied and harmonized with additional agricultural land management improvements. Best management practice principles indicate that efficient plant nutrient uptake, occurring along with reductions in nutrient input, will require improvements in agricultural technology such as slow release fertilizer or improved tillage equipment (Baligar et al., 2001; Bruuslema et al., 2008; Fixen, 2009). Inclusion of best management practices, combined with knowledge of local ecological systems, may help improve the relationship between agricultural nutrient inputs and infield productivity.

International analysis and comparisons of fertilizer use practices have found that crop yield is not solely correlated with the mass of fertilizer applied; instead crop yield is influenced by multiple other agricultural factors within agricultural lands (Baligar et al., 2001). One example of these complex interactions, that determine crop productivity, occurs when nitrogen uptake is improved because of high water availability. In this situation water is not in high demand, but the presence of water results in greater nitrogen uptake (Ittersum and Rabbinge, 1997). This example demonstrates how the use efficiency of agricultural nutrient inputs can be improved through the intentional promotion of positive interactions between agricultural multiple inputs other than supplemental nutrients. This concept is important because it supports the idea that the relationship between yield and fertilizer input mass is not exclusive and can be influenced
by many other agricultural system inputs. If optimal agricultural nutrient use is to be achieved, reductions or increases in phosphorus input should be met and coordinated with system level best management practices (Ittersum and Rabbinge, 1997; Bruuslema, 2008).

### 4.4. Environmental and sustainability implications

Analysis of phosphorus use efficiency, specifically phosphorus partial nutrient balances, is important because it can identify areas of inefficiency, reduce the risk of nutrient loss from cropping systems, and ensure the availability and quality of future phosphorus resources (Syder and Bruulsema, 2007; Bruuslema, 2008; Tilman, 1999; Smil, 2000). Globally about one third of land based ecosystems are in agricultural production and within the United States 52% of the total land mass is being used for agricultural purposes (Tilman et al., 2001; Lubowski et al, 2006). The sheer area of land under agricultural production and receiving fertilizer input represents a massive future need for phosphorus.

Increased food production, aided by agricultural nutrients, has allowed global food production to increase at a rate greater than global populations (Tilman, 1999). Over the last 35 years increases in global food production have been met with a 3.48-fold (Tilman, 1999) increase in phosphorus fertilizer input. Global phosphorus application rates, on preexisting agricultural land, have been steadily rising with increases in global GDP and population (Tilman et al., 2001). The significant mass of phosphorus being applied and the relationship between nutrients and yield is important because leakage of phosphorus from cropland is connected with damage to natural systems (Tilman et al,
For environmental reasons, the rise in nutrient input level and imbalance between nutrient input and removal is important because it increases the volume of phosphorus that may accumulate in off-field ecosystems. Increasing quantities of phosphorus eroding and flowing off of agricultural land is problematic because high rates of phosphorus entering non-agricultural terrestrial and aquatic environments can encourage growth of nuisance plant species and aquatic algal blooms (Tilman, 1999; Sharpley and Withers, 1994). The impacts of introducing additional phosphorus into aquatic and terrestrial ecosystems can be long lasting and can drastically reduce overall environmental health. To alleviate this problem, nutrient management improvements are necessary to improve nutrient use efficiency, reduce erosion, and reduce sub-surface phosphorus flows into aquatic resources (Tilman, 1999; Bruuslema et al., 2008).

Sustainability involves the preservation of future resources so that outputs can be maintained with the same level of input (Bruulsema et al., 2008). Phosphorus is a unique agricultural input is because global supplies of phosphorus are limited by known phosphate reserves and geological time scales (Cordell et al., 2009). Limited global supplies and access to phosphorus necessitate the need for conservation of this non-renewable resource (Cordell et al., 2009; Bruuslema et al., 2008; Tilman, 1999). In order to cope with increasing demand and decreasing supplies of phosphate fertilizer, use efficiency must be maximized by balancing phosphorus removal with fertilizer input. Evidence presented in this study indicates how the balance between input and removal can be improved. Knowledge about the balance between fertilizer input and nutrient removal can serve as an agricultural performance indicator and help to reduce off-field nutrient accumulation while preserving phosphorus resources for future use.
4.5. Policy & Economic implications

The findings of this study help to justify potential policy intervention. Trends in current phosphorus fertilizer use show that phosphorus inputs through manure and fertilizer are being applied to agricultural lands in quantities greater and less than removal rates. In the majority of instances phosphorus is being applied in a greater quantity than what is being replaced. In terms of public policy, current trends in phosphorus use represent a financial market failure because environmental damage caused by excess phosphorus flows into the aquatic environment are rarely accounted for in costs to producers or consumers (Bardach, 2009). Another reason why surplus phosphorus application is a problem is because known phosphorus reserves are limited and phosphorus is considered a non-renewable resource (Suh and Yee, 2011). Consumption of this non-renewable resource is problematic is because current use trends may impact and limit future agricultural practices and productivity. The evidence based market failure and externality indicate that public policy intervention may have the ability to meliorate the problems associated with imbalanced agricultural phosphorus use. It is outside the scope of this study, but public policy focused on target oriented agricultural nutrient management may be able to reduce phosphorus flows to the environment and reduce the consumptive burden on phosphorus reserves.

In addition to policy problems associated with phosphorus use, imbalanced phosphorus application and removal can result in unintended financial losses. Financial losses during agricultural production can occur during nutrient input, removal, or both. The imbalance of phosphorus, found in this study, means that agricultural land managers
may not be generating as much revenue as possible (Bruuslema et al., 2008; Sharpley and Withers, 1994). Agricultural farm chemicals make up approximately 7 percent of total farm expenditures (USDA-NASS, 2011b). Fertilizer input expenses are considered to be one of the variable costs associated with production agriculture. Variable costs, such as fertilizer are important to agricultural land managers because they may change and may reduce the total farm expenditures (University of Minnesota, 2008; USDA-NASS, 2011b). Within the 48 states analyzed in this study, fertilizer input equates to roughly 20 billion dollars of annual expenditure (USDA-NASS, 2011b). Therefore it is clear that profitability may be improved by reducing phosphorus input costs or by increasing crop yield and earned revenue. Ensuring financial efficiency, related to agricultural nutrient use, is important because economic efficiency is strongly correlated with nutrient use efficiency.

4.6. Real world vs. hypothetical agricultural practices

Studies and quantitative analysis conducted in the field of agricultural production ecology attempt to standardize agricultural management factors. Analysis of agricultural production relies on data that does not completely represent real world agricultural systems. For instance, this study conducted analysis exclusively based on agricultural harvest and input data from only one growing season. Real world production agriculture is extremely complex and the relationship between inputs and output cannot be completely reflected by agricultural production ecology. Real world agricultural conditions, such as weather and temperature, can impact biological grown and nutrient uptake. Land managers may seek to capitalize on nutrient costs in one year and over-apply phosphorus; and then the next year they would under apply because of the nutrient
content already in the soil. Additionally, farmers may adjust many other agricultural management factors to reflect real world economic conditions. Traditional economic theory suggests that farmers seek to maximize profit (University of MN, 2008). Temporal variation in crop demand or nutrient prices may motivate farmers to selectively plant crops and apply nutrients to meet economic goals rather than economic or sustainability goals.

Another important aspect of real-world production agriculture is that there is a significant possibility that nutrients will run-off of agricultural land. Phosphorus nutrients can run off of both uncultivated land as well as land under agricultural production (Sharpley and Withers, 1994). Research conducted by Sharpley and Withers (1994) has identified agricultural land as a major source of phosphorus into the environment. Therefore a complete balance between agricultural inputs and output is unlikely to occur. The fundamental equilibrium suggested when calculating partial nutrient balance is unlikely to occur because natural nutrient transport will move phosphorus off of where it was initially applied. The real world factors discussed here are important because they are very difficult to account for and quantify in partial nutrient balance calculations. The findings of this study need to be interpreted with the understanding that real world conditions will have a strong impact on nutrient balances.

4.7. Limitations, further research, and improvements

The findings in this study represent an important start to understanding how phosphorus is used, but the findings only represent a start in efforts to understand and improve phosphorus use efficiency. Understanding the limitations of this study is
important because it can aid in guiding future research and strengthen the findings of this study. This study represents an initial and limited evaluation of state and county-level phosphorus partial nutrient balances. Data that has been used in this study is the most complete and current data available, but it is still limited because of data sampling and collection schedules.

If more time and resources were available the research conducted in this study would be improved upon by (1) improving temporal detail and (2) improving the range of temporal analysis. Continued and improved research in this field can aid in analyzing fluxes in agricultural nutrient balances and interactions between soil fertility and nutrient input. The nutrient input data being drawn upon in this analysis was collected by the United States Geological Survey using fertilizer sales, fertilizer expenditure, livestock populations, and human population data (USGS, 2006). The temporal scale of this data is restricted by years that the Census of Agriculture is conducted (USGS, 2006). This significantly limits this study because the Census of Agriculture only occurs in five year intervals. Additionally the amount of farms surveyed, by the Census of Agriculture, is limited and may not completely represent actual nutrient applications. Expanding the temporal range of this study will help analyze how phosphorus inputs and soil fertility are related. Changes in fertility and agricultural management practices that occur in between sample years may impact nutrient removal and input values. Specific agricultural management practices like complex crop rotation, use of agricultural land for fallow, and other land management practices may not occur on a yearly basis, but may drastically impact the relationship between phosphorus input and removal (Bruulsema et al., 2008;
Sharpley and Withers, 1994). For instance, crops which have undergone recent rotation may exhibit drastically different soil fertility and may require less nutrient input to produce high crop yields. Another reason why improvements in temporal data are important is because development of more modern cropping practices and technology may affect phosphorus use and may not be fully accounted for in this study.

The research conducted in this study could also be improved upon by incorporating multivariate statistical analysis of many agricultural inputs, rather than just phosphorus fertilizer. Research in this study is only focused on nutrient inputs even though many inputs can affect agricultural productivity. Only analyzing nutrient input is problematic because it does not represent real world agricultural situations and cannot explain how additional factors impact crop yields. In the context of sustainability, phosphorus reductions may require increased inputs of other agricultural variables, therefore it may not be a good decision to restrict or reduce phosphorus inputs. Increased use of other agricultural inputs may have adverse environmental effects that may rival the impact of phosphorus use. Further analysis of this kind may aid in improving our understanding of how agricultural inputs are interconnected and work together to determine agricultural productivity. 22 major crops were analyzed in this study, but many other crops are commonly grown and receive phosphorus fertilizer application. Inclusion of every crop receiving nutrient application would help strengthen the findings of this study because it would offer a more complete picture of how nutrients are used in United States agricultural practice. Along with the inclusion of more agricultural production factors, this research could be aided by background knowledge reflective of market conditions and environmental conditions that may impact biological growth and

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nutrient uptake. Improvements to the research conducted in this study will help increase the use, strength, and application of agronomic indices and nutrient use efficiency metrics.

5. Conclusion

As agro-food production systems become increasingly relied upon to support the growing global population, improved resource management will be a crucial step in promoting efficient use of phosphorus and sustainable agricultural systems. The objectives of this study were to (1) determine phosphorus use characteristics at the national level and (2) determine temporal phosphorus use trends within individual counties in Minnesota. Previous research analyzing phosphorus flows (Suh and Yee, 2011) has led this study to hypothesize that phosphorus inputs and removal will not be balanced. Evaluating the phosphorus partial nutrient balances in the context of individual states and counties has shown that phosphorus inputs and removal is rarely in balance. Analysis of current national phosphorus use has shown that (1) phosphorus inputs into agricultural lands are both exceeding and falling below nutrient removal levels. Temporal analysis of Minnesota county-level partial nutrient balances has shown (2) that overall nutrient balances have improved between 1987 and 1997. Improved balance and use efficiency between nutrient inputs and removal is important because phosphorus is critical to many biological functions and known reserves of phosphorus are limited. In addition to our biological dependence on phosphorus, unintentional flows of phosphorus out of agricultural land into aquatic and terrestrial ecosystems are associated with eutrophication and other types of environmental damage. The analysis conducted in this
study exclusively looks at phosphorus inputs and output; it is important to understand how other on and off field conditions impact agricultural production. Under these circumstances and results, phosphorus use in the United States needs to be assessed and coordinated to balance phosphorus inputs with removal, minimize unintentional flows into the environment, and preserve this resource for future use.
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