CAN SOIL TEST PHOSPHORUS TRACK PHOSPHORUS CHANGES FOR WATER QUALITY MANAGEMENT?

A Thesis

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Master of Science

by

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ABSTRACT

Many Northeastern US dairy farms have surplus nutrients because of imported feed. The surplus accumulates in the soil and might affect water quality. Excess phosphorus is most problematic and has caused algal blooms in the drinking water supplies for New York City (NYC). NYC provides funding for reducing P losses from farms to water. This study assessed the effectiveness of this program in controlling P accumulation in soils. Over 1200 field soil sample series at least six years long with sampling at three year intervals were analyzed. The results indicate increasing Morgan's P in initially low P soils that is counterbalanced by decreasing Morgan's P in initially higher P soils. The breakpoint is around 12 kg P/ha. Regression analysis found increased Morgan’s P concentration with: corn frequency, higher recommended manure rate, and higher aluminum; and a negative effect of soil wetness. The soil status indicates that NYC watershed farmers have taken heed of nutrient management recommendations and supporting Best Management Practices.

BIOGRAPHICAL SKETCH

Steven Pacenka has assisted the public in finding rational, efficient, and effective solutions to complex environmental problems since 1975. From roots in New Jersey, USA, he began specialized training via a 1977 BS in Environmental Resources Planning from Cook College of Rutgers University. An internship with the New Jersey Department of Environmental Protection provided learning and professional practice experience from 1975 to 1977. He relocated to New York and continued education in 1977 with coursework as part of the MS Program in Environmental Systems Engineering at Cornell University. He could not resist the return to public service in 1979 as an extension and research water specialist with Cornell's Center for Environmental Research, later the Center for the Environment, and until 2007 the Department of Earth and Atmospheric Sciences. He resumed MS studies at Cornell in late 2007, concurrent with a research, teaching, and extension specialist role in Cornell's Department of Biological and Environmental Engineering. Besides the Cornell affiliation, he has provided environmental management services via volunteering with Finger Lakes Reuse, volunteering with Sciencenter, and consulting with Delaware County NY's Department of Watershed Affairs.

To the family farmers of Delaware County, New York, unappreciated health protectors of New York City's millions.

ACKNOWLEDGMENTS

The U.S. Environmental Protection Agency funded (in part) development of the "Cross-Farm" database until 2007, through the New York State Department of Environmental Conservation (NYS DEC) and the Delaware County (New York) Department of Watershed Affairs. Cost sharing was provided by Cornell University and the Delaware County Soil and Water Conservation District (SWCD). Mr. Keith S. Porter was Cornell Principal Investigator for the database contracts. The Cornell University Employee Degree Program paid two semesters of graduate school tuition and fees in 2007-2008, supporting thesis writing.

Dale Dewing, Cornell Cooperative Extension of Delaware County, collaborated with the MS candidate in the original Cross-Farm database project design, and provided insight into the Watershed Agricultural Program's nutrient management process. Magda Day, now retired from the Delaware County Soil and Water Conservation District, collaborated in database assembly, led GIS interfacing, and supervised map digitizing and data proofreading. Dr. Jery Stedinger guided the application of statistical methods. Dr. Tammo Steenhuis provided insights about soil phosphorus behavior. Drs. Stedinger and Steenhuis served as the MS candidate's Special Committee starting in 2007, as well as inspirational colleagues since the 1970's.

Additional local partners in the Watershed Agricultural Program and Delaware County included: Rick Weidenbach, Dean Frazier, Jim Hilson, Kim Holden, John Thurgood, Brian LaTourette, Kelly Blakeslee, Tom Hilson, Alan White, Dan Deysenroth, Brian Caruso, Larry Day, and Jim Eisel.

Database interns and staff in Walton included Lindsay Fisk, Jackie Hitt, Sheena Roberts, Joseph Miller, Sarah Thurgood, Melissa Fraser, and Kevin Youngers. Cornell student database programmers were Siwing "Ivy" Tsoi and Corey Boland. Ms. Tsoi did the project's first phosphorus change maps to provide a working target.

Watershed farmers who inspired the MS candidate's work in Delaware County included Jim and Barb Robertson, Richard and Holley Giles, Stubby and Marian Ploutz, and Tom Hutson.

New York City Department of Environmental Protection watershed modelers Mark Zion and Elliot Schneiderman influenced key aspects of the database structure. Zach Easton of Cornell Biological and Environmental Engineering provided a digital map of soil topographic index values for the Cannonsville Basin.

Ken Markussen, Bruce Mussett, and Pat Bishop were on NYS DEC's side of contracting and funding. Linda Brainard and Pat Garrett provided Cornell's contract and financial administration before 2007. Peggy Pilch and Sandy Whittaker were their SWCD counterparts.

Cornell Agronomy retirees W. Shaw Reid, Dave Bouldin, and Stu Klausner provided insights about soil test phosphorus in NY and the algorithms used in making recommendations for fertilizer and manure nutrient application.

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1. Introduction

The Problem of Phosphorus Accumulation in Dairy Farm Soil

Many Northeastern US dairy farms have had phosphorus mass imbalances because they bring in much more phosphorus in the form of feed and fertilizer than they send out in dairy products and meat (Cerosaletti *et al.*, 2004). The surplus ends up accumulating in soil due to manure spreading. By 2001 almost half of the soil samples Cornell University tested for New York farmers fell into the "high" or "very high" phosphorus ratings for crop production, up from a stable 25% in the 1950s through 1970s (Ketterings et al., 2005). It is well known that concentrations of soil phosphorus in easily mobilized forms correlate positively with phosphorus concentrations in farm runoff water (Vadas *et al*, 2005), thus runoff from farm soils can contribute to eutrophication of downstream phosphorus-limited lakes and reservoirs (Vollenweider, 1968; US EPA, 2009). Increasing soil phosphorus in these forms implies increasing phosphorus loadings to lakes.

Thus managing phosphorus-sensitive watersheds that include extensive farmland should include managing soil phosphorus of the easily mobilized forms. This document explores how to use agronomic soil phosphorus data from a watershed management program to evaluate how well soil phosphorus has been managed.

Controlling Agricultural Phosphorus in the New York City Watersheds

The locally operated Watershed Agricultural Program (WAP) protects unfiltered New York City water supply sources in New York's Catskill Mountains. The West-of-Hudson area's farms are predominantly family-scale livestock operations, with a majority of dairy and some beef (USDA, 2008). Area farmers typically use purchased feed and grow their own grass and corn in rotations. Grasses and pasture dominate active field acreage. Voluntarily involved farmers and WAP staff have created and maintained standard nutrient management plans, as well as other nutrient-related Best Management Practices (BMPs) ranging from barnyard paving to livestock feed changes. Some of the farms entered the program as early as 1992, and thus have two decades of experience in the program (Ad Hoc Task Force on Agriculture and New York City Watershed Regulations, 1991; Watershed Agricultural Program for the New York City Watersheds, 1997).

Focusing especially on the Cannonsville Reservoir basin (Figure 1), the program has contributed materially to a reduction in dissolved phosphorus loading to the reservoir, according to water quality monitoring and modeling results. WAP's coordinated BMPs at one showcase farm yielded a 43% reduction in dissolved phosphorus loadings during events (Bishop *et al.*, 2005). The great expense[*] of measuring highly transient runoff has allowed direct measurements of runoff quality at this site, but few others of the hundreds involved. Calibrated models provide indirect evidence of a 41.5% reduction in dissolved phosphorus loss from ongoing farms in aggregate for the Cannonsville watershed (Cowan, 2008; similar to unpublished findings by

[*] It cost over US$100,000 (excluding some labor costs) to establish a continuous water quality monitoring station at one Catskills farm site and tens of thousands of dollars per year to maintain it and analyze its samples (Bishop, 1999-2007 personal communications).

Schneiderman and Zion, 2006). When using water quality data from this large basin it is a challenge to distinguish improvements in active farm runoff from a concurrent decline in watershed agriculture.

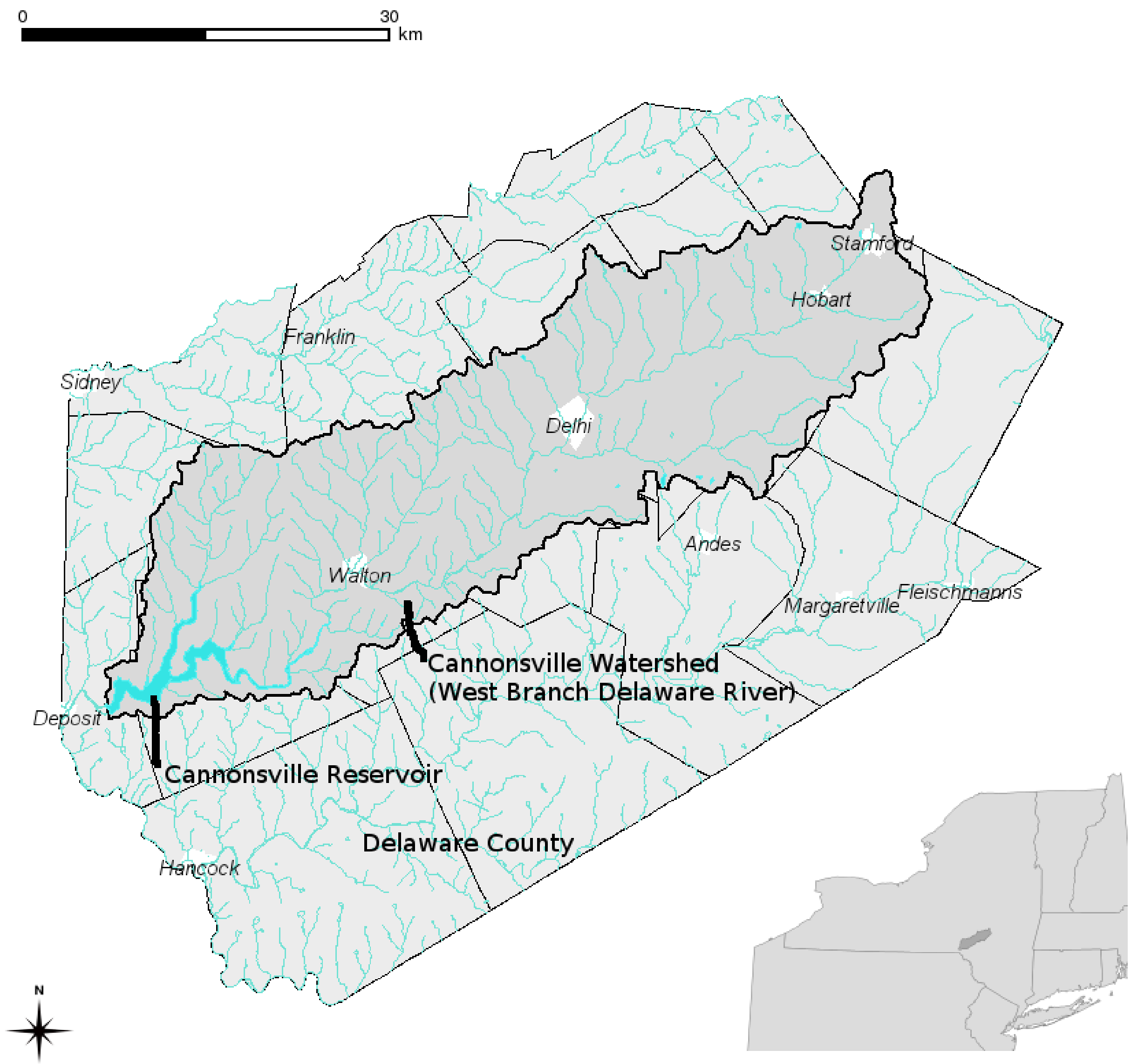

Figure 1: Cannonsville Reservoir watershed in northeastern US

WAP's soil phosphorus management has been extensive and presumably contributed to the loading reductions. WAP's nutrient management plan (NMP) database through 2007 contains measured soil phosphorus for over a thousand fields at multiple times, many of which have been in the program for over six years. This unusual data set could yield insights about how to manage phosphorus to protect water quality in the livestock farming areas of the northeastern US and beyond. This document extracts trends in soil test phosphorus (based on Morgan's extractant) from the database and correlates them with field characteristics and management recommendations.

Motivation for Environmental Phosphorus Management

Water quality regulators and other watershed managers have been attempting to reduce phosphorus loads to inland watersheds for decades, because of the association between phosphorus and eutrophication of freshwater lakes and reservoirs. Besides aesthetic and ecological concerns that motivated the earliest eutrophication control, more recent public health concern about drinking water disinfection by-products has added impetus to reduce reservoir eutrophication. The presumed linkage is that eutrophic water bodies have higher concentrations of by-product precursor compounds, which increases the chance that chlorination will form undesirable by-products (Oliver and Schindler, 1980). Regulatory concern is greatest for unfiltered surface water supplies (US Environmental Protection Agency, 2009). When higher concentrations of by-product precursors are present, backing off on chlorination could pose risks of pathogens surviving treatment -- whereas increasing chlorination increases the risk of cancer. To avoid this Catch 22 dilemma, an unfiltered supply must control the precursors.

New York City's west-of-Hudson water supply system does not include filtration treatment, by special Federal and State permission. Their watershed protection programs in the Cannonsville basin have invested tens of millions of dollars in wastewater treatment system upgrades and tens of millions of dollars in nutrient management improvements on hundreds of small farms (NYC DEP, 2006). Phosphorus received high priority for control and reduction due to the history of eutrophic conditions in the reservoir.

Related Work

Trends in worsening mass nutrient imbalances on agricultural land have raised concerns about the eventual escape of excess nutrients from farms into water. Withers *et al.* (2001) estimated an average total soil P accumulation of 15 kg ha^{-1} yr^{-1} over the period 1935-2000 across all grassland and arable area of the UK. Delaware County NY (Board of Supervisors, 1999) estimated a 20 kg ha^{-1} yr^{-1} total P accumulation for fifteen farms around the time of the establishment of the Watershed Agricultural Program. Uusitalo *et al.* (2007) report that Finland's 1980's net imbalance of +35 kg ha^{-1} yr^{-1} declined to +8 kg ha^{-1} yr^{-1} by 2005, after government controls and taxes were tightened in response to concerns over water quality effects of increasing soil phosphorus. Mass nutrient balances seem less tracked in the US than in Europe, but trends in soil test P are tracked. Wisconsin (Peters, 2011) found that their mean Bray-extractant P levels nearly doubled from 1964 through 2000-2004 then declined slightly by 2005-2009. New York's findings of Morgan's P increase in 1981 through 2001, cited above, helped to focus management attention in critical watersheds like the Delaware and Susquehanna River basins.   Back in Finland, Uusitalo *et al.* (2007) found a drop in their acetate-P (similar extractant to Morgan's, about 70% greater concentrations than from Morgan's extractant) from 11 mg L^{-1} soil median in 1997 to 9 mg L^{-1} in 2002 across 1600 fields (assumed to be mostly cereal crops) for which time series samples were available. This was a significant drop at the 95% level using the Wilcoxon signed-rank test. They further modeled the relationship between mass balances and soil acetate P change, then reconstructed soil acetate P history to infer a peak around 1995-1997 following increases from 1985, then a decline as the mass balance surplus was cut by over 75%. The Finnish work clearly establishes that a total P mass imbalance will definitely translate into increases in a soil P measure similar to New York's, and that soil P can begin to be brought under control by a major reduction in the mass imbalance.

The linkage between soil test P measured with certain extractants and P losses from fields by runoff has a similarly robust basis. Andrew Sharpley and former colleagues of USDA-ARS have persisted in work in this topic area since the 1980s and published much useful material. Vadas *et al.* (2005) integrated data from many experiments on phosphorus washout by runoff in the form of extraction coefficients, which are the slopes in linear correlations between reactive phosphorus concentrations in runoff and extractable soil phosphorus concentrations. In particular they took into account the degree of phosphorus saturation of available iron and aluminum sorption potential in noncalcareous soils. Sharpley in particular has contributed to understanding the forms of soil and manure phosphorus mobilized by runoff water and how to measure them (Sharpley, 1993; Sharpley *et al.*, 1984; Sharpley and Moyer, 2000), and to integrating field research into practical recommendations for agricultural environmental management (Sharpley *et al.*, 1996). Pote *et al.* (2003) cited Sharpley when stating that several States have begun to recommend shifting animal manure applications from high P soils toward low P soils for water quality reasons.

Roles of Remaining Chapters

This thesis contains four additional chapters. Chapter 2 provides background about several topics: how soil phosphorus is measured, farm mass nutrient balances, how phosphorus is managed in a northeastern US setting, and the expected trajectory of phosphorus change on WAP's cooperating farms.

Chapter 3 explores the statistical properties of an excerpt from WAP's across-farm, time-series, field-level nutrient management database. It emphasizes how soil test phosphorus has changed overall between when farms joined the program and when they had at least six years of experience with the program.

Chapter 4 explores relationships between soil phosphorus changes and field attributes including chemistry, recommended manure use, and soil wetness. Regression models allow exploration of whether each attribute has a statistically significant effect on changes in Morgan's soil phosphorus, and whether that effect is to increase or decrease phosphorus content. A standard regression analysis is used with high outliers removed, and a robust regression analysis is also applied.

Chapter 5 provides a final discussion and overall conclusions to this study.

This work is applicable in New York's Catskill mountain region and in other field-crop, livestock farming areas where:

- A database of agricultural soil phosphorus has been accumulated, covering hundreds of fields over at least two soil sampling cycles, and including cropping history, soil type, fertilizer and manure management, and soil chemistry;
- The soil phosphorus measurements use a weak extractant like Morgan's sodium acetate, which is well correlated with runoff quality; and
- There is an active and well documented attempt to manage phosphorus for water quality protection, via nutrient management planning, manure use planning, or livestock feed adjustments.

2. Phosphorus in Livestock Farm Soils

This chapter summarizes aspects of soil phosphorus forms, measurement, and management in livestock farm soils. This background information is needed to help interpret soil test phosphorus measurements and their changes over time. The chapter closes with an expected time trajectory of soil phosphorus in the Cannonsville basin.

Soil Phosphorus and Soil Test Phosphorus

Phosphorus in a dairy farm's soil exists in various states, from dissolved phosphate in soil water to insoluble compounds within rock fragments. For an excellent overview of forms and their measurement, see Herlihy and McCarthy (2006). Figure 2 provides a conceptual model dividing stored phosphorus into four classes, "solution P", "P sorbed on Al, Fe", "Plant P", and "other P forms." These classes are oriented toward the agronomic, empirical phosphorus extraction process used in making fertilizer recommendations for crop production.

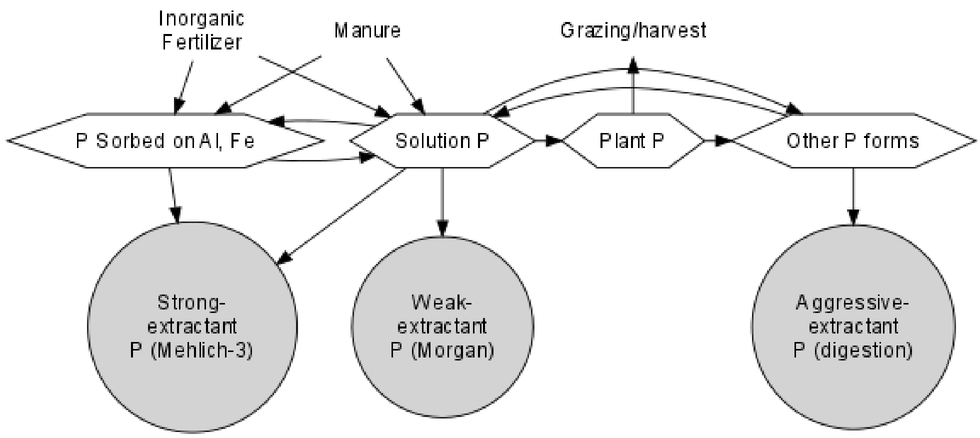

Figure 2: Extraction-oriented schematic of phosphorus forms and related transfers

"Soil test phosphorus" is a generic term covering a variety of specific methods of extraction and processing. Different extractants are used in different jurisdictions to determine soil's agriculturally important phosphorus content. Table 1 summarizes the seven extractants referred to in this document, including which northeastern US States use which extractants and the results of a cross-State collaborative experiment on relative phosphorus recovery (Heckman *et al.*, 2006). The region's soil parent materials range from glacial debris to unglaciated rock, precambrian mountain roots to recent coastal plains and alluvium.

Table 1: Comparison of soil phosphorus extractants

Method	References	Reagents	Northeast US median in Heckman *et al.*, 2006 (ppm)	Northeast US users circa 2006
Morgan	Morgan, 1941; Peech and English, 1944	NaOAc[†] HOAc	5.5	NY, RI, MA
Modified Morgan	McIntosh, 1969	NH_4OAc	3.7	VT, ME, CT, RI
Mehlich-1	Mehlich, 1953	HCl H_2SO_4	43	NJ, MD, WV
Bray-1	Bray and Kurtz, 1945	HCl NH_4F	83	PA (former)
Mehlich-3	Mehlich, 1984; Wolf and Beegle, 1995	HOAc NH_4NO_3 NH_4F EDTA	81	PA, NJ, DE, NH, MD
Finnish acetate	Vuorinen and Mäkitie, 1955 as cited in Saarela, 2002	NH_4OAc HOAc	n/a	n/a
Olsen	Olsen, *et al.*, 1954	$NaHCO_3$	n/a	n/a

New York's soil testing convention for field crops specifies the Morgan procedure, which largely extracts phosphate ions in solution, and extracts little of the phosphate that is sorbed on soil iron and aluminum. Other methods cited in Table 1 extract sorbed phosphorus and possibly more. Figure 2 compares the Heckman *et al.* results for 51 farm field soil samples using five different methods. The stronger extractant Mehlich-3 yielded over 15 times higher P from soil compared to the weaker Morgan's extractant. An ultimate extraction involving acid digestion of finely ground soil can be used to determine essentially the total soil P, which can reach a thousand kilograms or more per hectare in the top 15 cm of soil (Brady and Weil, 1996). Morgan's extractable P -- measuring what plant roots can take in from solution easily -- represents a small fraction of the total soil P.

[†] The "OAc" symbol represents the acetate ion, $CH_3CO_2^-$.

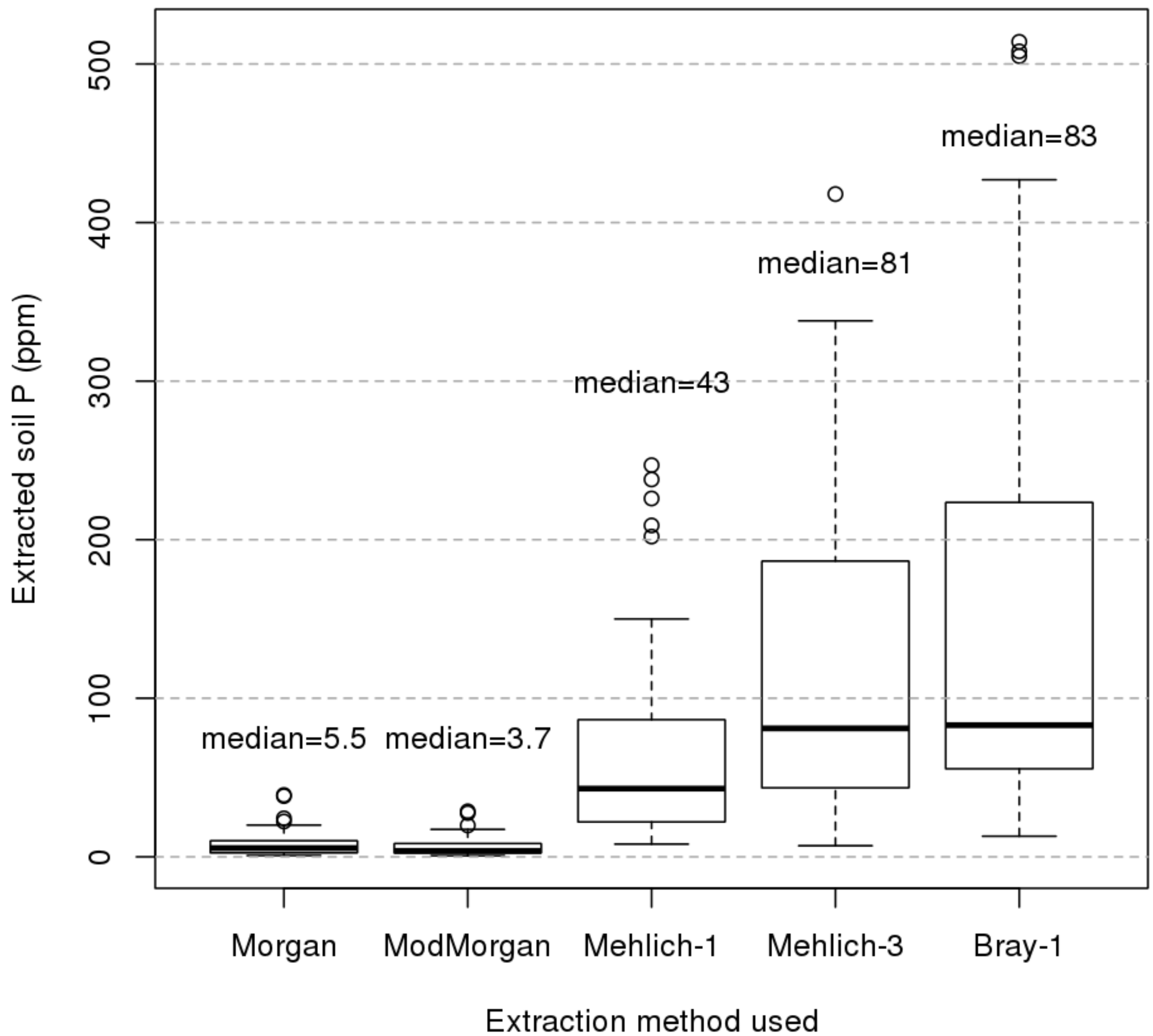

Figure 3: Phosphorus in 51 Northeastern US soils using different extractants (data from Heckman *et al.*, 2006)

Additions of mineral fertilizer or manure provide an initial rapid boost to "solution P" (and thus Morgan's extractable P), but in incubation studies blocking plant uptake the solution P concentration declines steeply within days as some of the dissolved phosphate sorbs to aluminum and iron, and more becomes incorporated into the "other soil P" pool via conversion into organic forms. (In an alkaline soil there may also be losses of added P due to precipitation of calcium phosphate compounds.) The fraction of added P that remains in solution depends heavily on the initial soil test P, as measured by Morgan or another weak extractant (Pote et al 2003; Griffin *et al.*, 2003; Haden *et al.*, 2007). Initially P-deficient soils need more P added to cause a unit rise in solution P than do soils that already have ample P in solution or sorbed forms; remaining unused sorption capacity of the soil's iron and aluminum in the P-deficient case will draw much added P out of solution. The total capacity of a given soil to sorb phosphorus is called the phosphorus saturation point (and sometimes the "change point"). Kleinman *et al.* (1999) and Kleinman (1999) found an average saturation point in the noncalcareous soils of the upper Delaware River watershed of 35 mg Morgan's-extractable P kg soil^{-1}, which is equivalent to 78 kg ha^{-1} at New York's customary bulk density 1.44 g cm^{-3} and customary 15 cm soil depth. Beyond the saturation point, added manure or mineral fertilizer P would tend to stay in a dissolved, unsorbed, and very water-mobile form.

In a manure-surplus area like a Catskills dairy farm, a practical water-quality application of the phosphorus sorption potential of soil is to direct extra manure away from high phosphorus fields that near or exceed their saturation level, and toward fields far below the phosphorus saturation level. While the soil remains well below its saturation level, it can sequester some phosphorus from leaching and runoff. It would also sequester the extra phosphorus from Morgan's extractant. A supplemental phosphorus extractant would be needed in a Morgan-using area like New York to determine sorbed phosphorus that may later be desorbed and remobilized to water.

Soil Test P Inherent Variability

A single soil sample is assumed to represent the annual average, spatially averaged condition of an entire field to a 15 cm depth. The data are inherently imprecise, and are rounded into ranges for their primary use in fertilizer recommendations. Table 2 shows the ranges used for making recommendations in New York, and Table 3 identifies factors that limit how representative a single 10-20 core composite sample may be of the field's annual spatial mean.

Table 2: Cornell agronomic soil test phosphorus classifications

Level (ppm)	**Level (kg ha^{-1})**	**Classification**
<0.5	<1	Very low
0.5-1.4	1-3	Low
1.5-4.4	3-10	Medium
4.5-19.9	10-45	High
>=20	>45	Very high

(Source: Ketterings *et al.*, 2005; original uses lb/acre rather than kg/ha)

Table 3: Sources of variability in field soil test phosphorus

Aspect	**Attempted Control**
Lateral spatial variation within field	Compositing 10-20 cores, choice of core location in light of visible field topographic and other variation
Vertical variation	Cores to standard depth (15 cm)
Seasonality	Consistent season
Recent manure, fertilizer, or lime application	Preferred sampling in fall, not soon after most recent treatment
Sample holding until analysis	Limited time, chilling; consistency, calibration of agronomic recommendations to measurements based on same standards
Screening, drying, mixing	Long term standardization; calibration
Extraction	Long term standardization; calibration
Chemical analysis	Long term standardization; calibration

Based on: Cumulative personal communications with WAP, S. Klausner, W. S. Reid, and D. Bouldin, 1992-2007.

Sampling for soil P can be a challenge in the Northeast US region because the spatial heterogeneity of physical and chemical conditions within sloping upland fields. A high-resolution, discrete soil sampling experiment in New York corn fields found that at least 30 discrete sample results had to be averaged to get within 10% of the high-resolution field mean of Morgan's phosphorus with over 90% confidence (Grandt *et al.*, 2010). For pastures in the Arkansas highlands, Daniels, *et al.* (2001) found that Mehlich-3 P content required 12-35 samples to get within 10% of the high-resolution field means with over 90% confidence. The agronomic field sampling recommendation for New York for field crops is 10-20 composited cores.

Given that spatial heterogeneity is only part of the list in Table 2, it is evident that individual sampling results in the WAP database have a notable, but unquantified measurement variability. Agronomic uses of the data take this variability into account by using four ranges below the maximum.

Mass Balances, and Soil P Responses to Imbalances

Mass nutrient balances can be used for environmental impact assessment, reasoning that losses of a soil nutrient to water correlate with a mass balance surplus on a farm (Öborn *et al*, 2003). Mass balances are in terms of total phosphorus, rather than a partial extractant like Morgan's. Controlled 10-15 year experiments using mineral fertilizer on grass, cereals, rapeseed, and potato in Finland found that soil total P rose in tandem with the mass balance surplus of fertilizer minus crop yield (Saarela *et al.*, 2004). Table 3 summarizes the very instructive Finnish data. These are adjusted for zero-fertilizer control fields, and represent the net effect of adding 45 kg ha^{-1} of mineral fertilizer in each year over the long experiments. This was considerably higher than plant uptake needs thus all fields accumulated notable total phosphorus (determined via strong acid extraction). Except in the organic outlier site 21, Olsen's agronomic extractant found 6-15% of the total P increase. Finland's agronomically-oriented acetate extractant, similar to the Morgan's extractant used in New York, found 1.5-7% of the total P increase, and a weak water extractant representing runoff found about the same as the acetate. Notable in the acetate and water cases are that soils initially higher in acetate-extractable P exhibited up to four times as much phosphorus increase using the two weaker extractants, compared to soils starting with lower acetate-extractable P. The stronger Olsen extractant did not yield such a pattern. The researchers attributed the influence of the initial P as demonstrating that added inorganic P in fertilizer was being sorbed in a way that was not extractable by the two weaker extractants but was extractable by the stronger two. Soils with higher initial acetate P were closer to their ultimate sorption capacity thus more of the added P would remain un-sorbed and be subject to mobilization by acetate or even plain water. Thus the mass balance surpluses in the P-deficient soils were potentially muted in their off-site effects compared to the higher initial P soils.

Table 4: Soil phosphorus changes after 10-15 year fertilizing experiments in Finland

Soil group	Initial Acetate P (mg dm^{-3})	Δ Total P (mg kg^{-1})	Δ Olsen P (mg kg^{-1})	Δ Acetate P (mg dm^{-3})	Δ Water P (mg dm^{-3})
Clay, loam, Low P	4.9	+207	+27	+4.1	+3.9
Clay, loam, High P	22.2	+240	+28	+14.6	+12.5
Sand, silt, Low P	5.8	+315	+18	+3.6	+3.3
Sand, silt, High P	29.3	+248	+26	+14.9	+17.2
Organic, MedP	9.1	+273	+39	+7.0	+12.1
Organic outlier 21	8.0	+120	+77	+8.3	+30.3
Overall	13.1	+253	+30	+8.8	+11.1

A "farm gate" type of total phosphorus mass balance is typically used when evaluating farms -- the bottom line surplus is the sum of imports minus the sum of exports with respect to the farm boundary. Losses from soil to water and minor imports and exports are neglected (Klausner *et* *al*, 1997). Figure 4 augments Klausner's mass balance diagram with some of the minor terms of interest in water quality assessment.

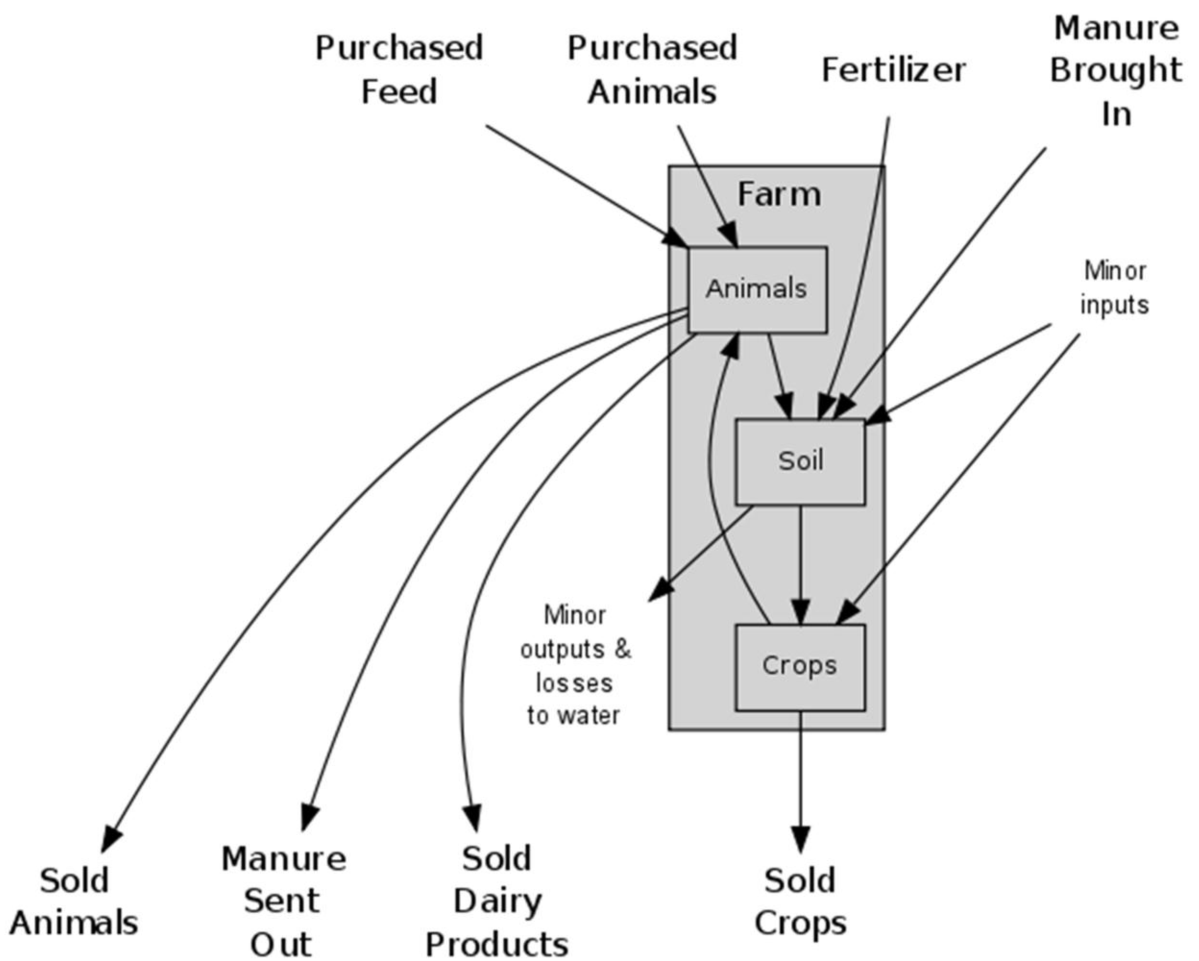

Figure 4: Nutrient mass balance of a small livestock farm (after Klausner, et al., 1997)

WAP began computing farm gate surpluses at its inception in the early 1990's, leading to early concern about their magnitude. Delaware County, with some WAP-related agencies, began striving to reduce farm gate surpluses around 1999, focusing on phosphorus in purchased feed (Cerosaletti *et al*, 2004; Delaware County Board of Supervisors, 1999). Estimated surpluses before 2000 were often over 50% and as much as 74% of the imported total. The surplus materializes within manure, then passes into soil when the farm spreads manure on cropped fields or livestock defecate on pastures. A recurring surplus on most farms implies a trend of increasing soil total phosphorus on average across farms and fields, estimated at 20 kg ha^{-1} $year^{-1}$ on the cropped land of fifteen farms having sufficient data to construct farm gate mass balances[‡] (Delaware County Board of Supervisors, 1999).

How Nutrient Management Tactics Affect Soil P

WAP's earliest structural BMPs for nutrient control nutrient control focused on eliminating rapid losses of manure organic matter to streams. These BMPs include rerouting milking center wastes into manure storages, excluding water from barnyards, relocating manure storages out of runoff prone areas, providing alternate water sources for livestock so they do not defecate and urinate into streams while drinking, and prescribing manure spreading schedules that would avoid the locations and times of year when spread manure was most likely to be washed away by rain or snowmelt. Even roads were built for nutrient management reasons -- to enable farther-away land to be reached by manure spreader vehicles. Most farms received some attention about manure handling, for both pathogen loss control and nutrient loss control. In sum these BMPs were expected to keep phosphorus on the farm longer -- thus building up more in storage unless inputs to the farm were cut, an aspect deferred until later in the program. They also had the

[‡] For fifteen WAP farms: 47 tons of 72 incoming were retained (65%); spread the surplus 47 tons/yr over 5200 field acres = 18 lb $acre^{-1}$ $year^{-1}$ (20 kg ha^{-1} yr^{-1}) total P accumulation. For six farms with the best data, the percentage retained was 48-74%.

effect of spreading available manure over a larger acreage within the farm than the farmer would have used earlier with poorer spreading equipment, poorer roadways, and poorer storages (Delaware County Board of Supervisors, 1999).

The program bought short term reductions in nutrient emissions at the possible expense of later increases. Cannonsville basin water quality modeling with SWAT by Tolson and Shoemaker (2004) assumed that the year-after-year mass balance surplus would continue, and with stable agriculture this would eventually lead to significantly increasing phosphorus loss to water. This could eventually cancel early gains from WAP's elimination of the quick-loss P sources.

Nutrient management plans (NMPs) are a nonstructural BMP that recommend fertilizer, manure, and lime additions field by field over one or more years. The methodology for preparing a NMP includes allocating available manure across fields, working from a farm total computed from herd size and manure nutrient concentrations. The recommended allocation -- to the extent that the farmer follows it -- can distribute a farm's annual surplus phosphorus away from fields with excessive P and toward fields with deficient P. Similarly mineral fertilizer P can be deployed taking account of individual field P status. With surpluses as large as cited above, redirection across fields via the NMP can help to control the impact of the total P surplus. (It should be noted that many high-P fields may still need manure to meet nitrogen needs.)

Later in the program, attention to the mass balance took the form of precision feed management (Cerosaletti, 1998; Cerosaletti *et al.,* 2004; Ghebremichael *et al.*, 2007). This scheme reduces the weight concentrations of N, P, and K in manure (mg of nutrient per kilogram of manure).

Thus a farm using this BMP would still produce and apply the same weight of manure to soil, but it would apply fewer kilograms of nutrients per hectare of land. Precision feed management began in the area in 1999 with a few demonstration farms, then began to ramp up in 2004 through 2007. Because of this calendar, precision feeding's effect on soil P would not yet have influenced many soil tests in the WAP nutrient management database which terminated in 2007.

Expected Trajectory of Soil P in active Fields

Ketterings *et al.* (2005) cited an all-New York change from 1976-1980 through 1996-2001: an increase from 26% to 47% in the fraction of samples over >9 lb/acre of Morgan's P. Figure 5 show that this was a new trend -- the fraction above the "very high" 9 lb/acre figure was stable from the late 1950's, 27%, to the 1976-80 period. The data sets cited by Ketterings *et al.* are large and diverse, particularly 1996-2001 which contains over 100,000 soil test results.

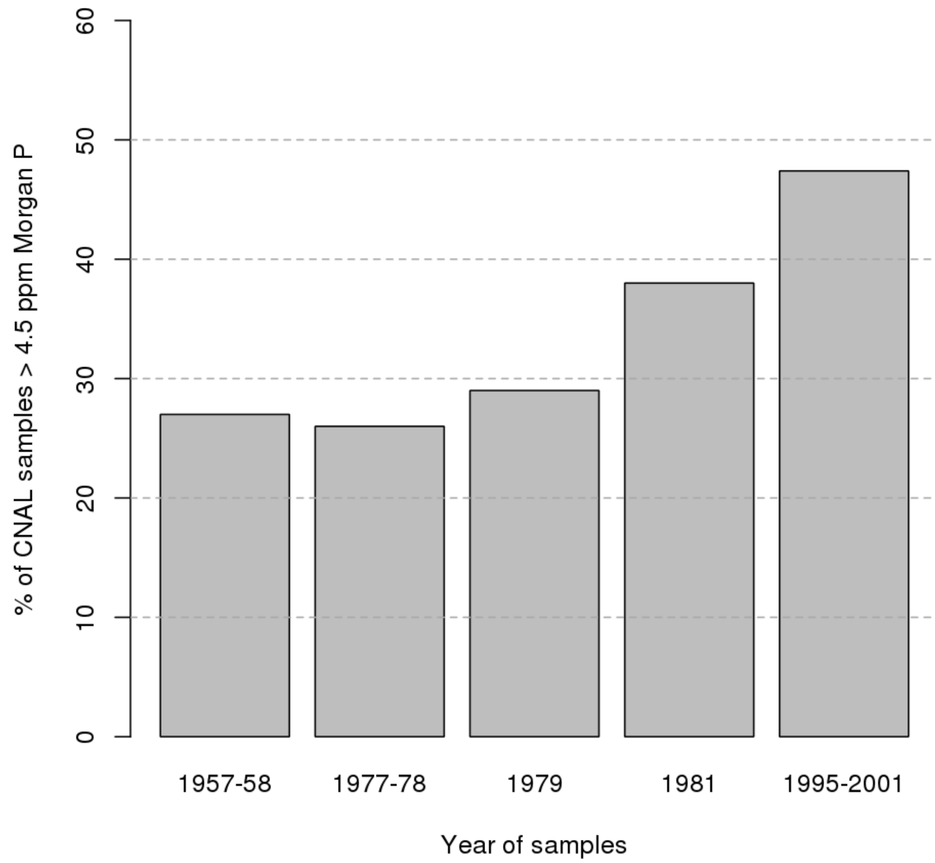

Figure 5: Trend in Morgan's soil P in samples tested at Cornell Nutrient Analysis Lab

The combination of local P mass balance surpluses, reduced rapid emissions of surplus P to water, and the 1980's-1990's trend of increasing Morgan's soil P in the rest of New York suggests that both soil total P and Morgan's soil P should have continued to increase in active Cannonsville farm soils, on average, through at least the mid 2000s.

3. Exploratory Analysis of Phosphorus Change

This chapter provides a basic overview of the demographics of WAP fields that have suitable records to evaluate phosphorus changes. It proceeds to explore observed soil phosphorus changes and candidate independent variables used in regression analysis in the following chapter.

Database Excerpt for Change Analysis

WAP's confidential cross-farm, time-series database merges all nutrient management plan files and maps that were available in a digital form dating back to the program's beginning in the early 1990's, through mid-2007. The overall database is documented in Pacenka *et al.* (2007). This study made an excerpt of data series about long-continuing fields to be able to interpret end-to-end phosphorus changes in light of what happened on the fields over the period, such as cropping changes. Table 5 shows the columns of this excerpt which contains one record per persisting field.

Table 5: Selected columns (variables) of excerpted field series data set

Name	Definition
P_i	starting Morgan's soil phosphorus (kg ha^{-1})
P_f	ending Morgan's soil phosphorus (kg ha^{-1})
$\Delta P/\Delta t$	end-to-end rate of Morgan's soil phosphorus change, (kg ha^{-1} yr^{-1})
Ca	Extractable (Morgan's solution) soil test calcium (ppm)
Fe	Extractable (Morgan's solution) soil test iron (ppm)
Al	Extractable (Morgan's solution) soil test aluminum (ppm)
OM	Soil organic matter (weight %)
FrCorn	Fraction of series duration in corn crop
ManRecY	Average recommended manure rate (gallons $acre^{-1}$ $year^{-1}$)
TempRegime	"upland" or "lowland" based on largest soil map unit classification for the field ("frigid" regime is upland, "mesic" regime is lowland)
Δt	Number of years between first and last soil sample for this field

Data Completeness and Quality

The field-level phosphorus change data set represents a consolidation from the entire collection of field-years within NMPs to focus on field series having at least two soil samples that represent the same area at different dates. In interpretations here, these data are filtered further to omit series with less than six years between the first and last samples of a series. The dark areas of

Figure 6 represent over 1000 fields having soil samples spanning at least six years. The entire shaded zone is based on fields that have at least one NMP and map in the database. The areas covered by maps that are lighter shaded may not have joined the program until after 2001, may have dropped out of farming less than six years after their first soil sample, or their earliest soil sample data or field polygon maps may be missing. The "persisting fields" are very geographically diverse, and represent the Cannonsville basin and WAP's constituent farms well.

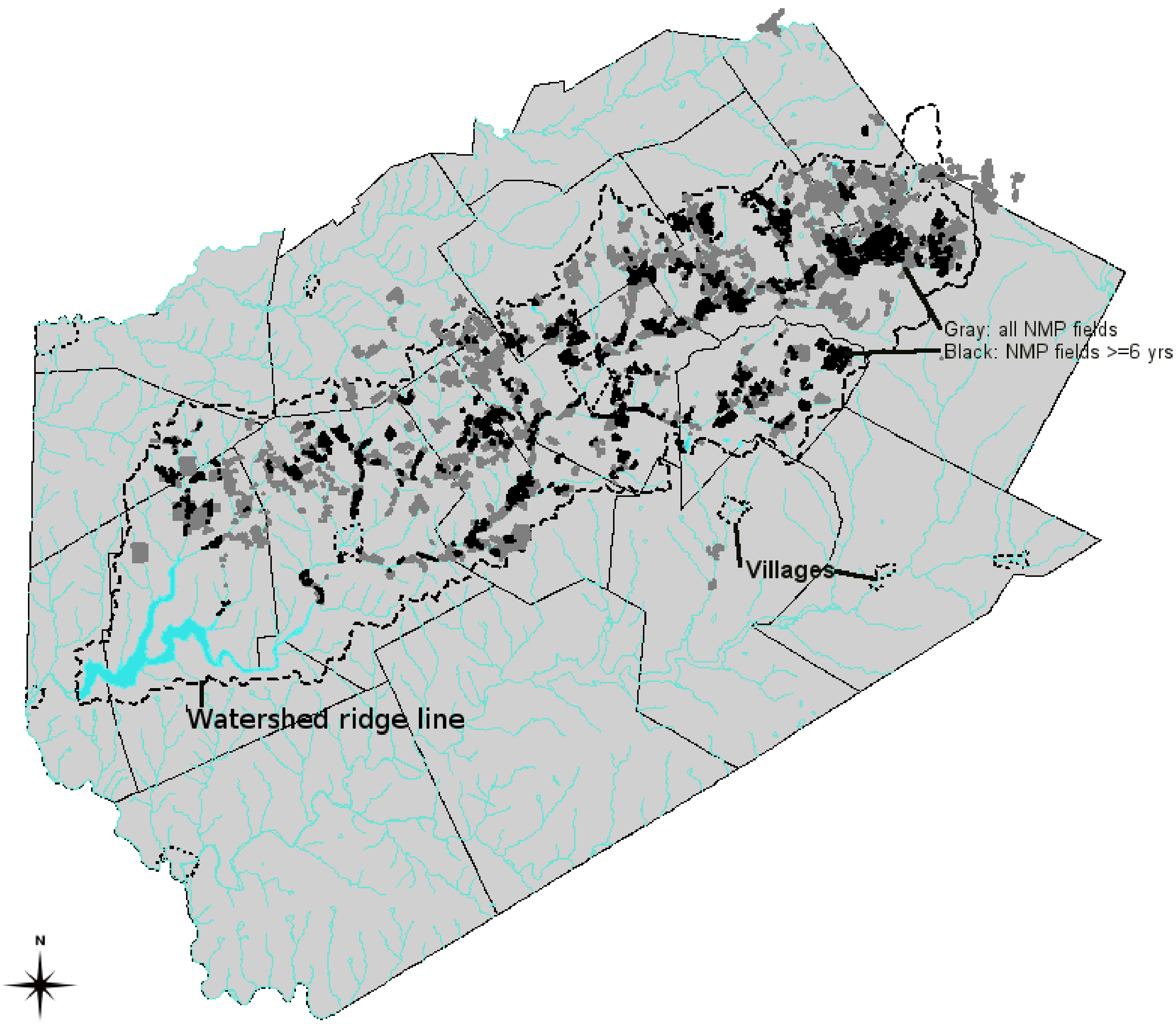

Figure 6: Fields covered by consecutive NMPs whose data persist for at least six years

Table 6 indicates that the data set covers 1216 field series, all of which contain initial and final Morgan's soil P change data. 747 records contain values for all candidate independent variables for regression analysis (Chapter 4).

Table 6: Record completeness in the field series data set

Constraint	**Number of Field Series**
>=6 yrs between first and last soil phosphorus test	1216
>=6 yrs, have Ca	1174
>=6 yrs, have Fe	1171
>=6 yrs, have Al	1174
>=6 yrs, have OM	1175
>=6 yrs, have crop (corn vs grass)	842
>=6 yrs, have recommended manure	781
>=6 yrs, have soil topographic index	1213
>=6 yrs, have upland vs lowland	1185
>=6 yrs, have all of the above	747

As shown in Figure 7, the bulk of the excerpted farms joined in 1994-1996. Figure 8 indicates that most excerpted series extend longer than six years. With interpretations restricted to a six-year minimum, and with the large majority of farms starting in that three-year window, nearly all of the asynchronous field series overlap in time for the majority of their years. As a simplifying assumption, the excerpted fields were pooled as if they all began their WAP experience at the same time; i.e. time is always counted from when the farm joined WAP. Durations remain important so most variables will be represented as fraction of total duration or rate per year.

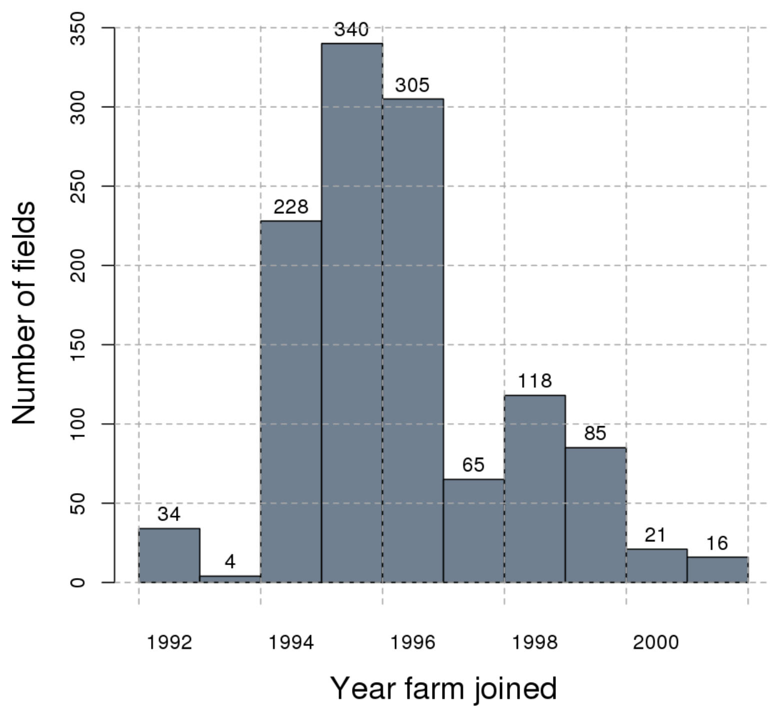

Figure 7: Fields by year farm entered WAP

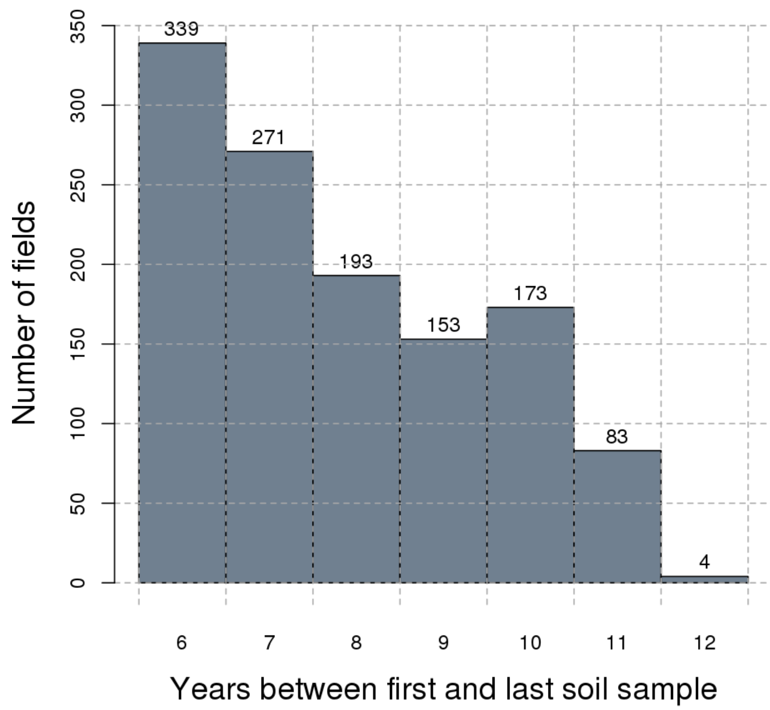

Figure 8: Durations of field series

Data quality for change analysis is constrained by the data's origin in nutrient management planning, which does not require high precision. Soil test results are subject to several forms of variability (noise), as discussed in chapter 2. Crop coding is subject to error by inexperienced field personnel. Actual manure application records within NMPs are only used qualitatively for nitrogen recommendations, thus the NMP’s recommended manure rates were chosen as a better approximation of actual rates. (There was no compulsion for the farmers to implement the recommendations.)

Status and Trend in Soil Test Phosphorus

Figure 9 indicates a large variety in Morgan's soil P when farms joined WAP. (As in the rest of this chapter, for simplicity the display units are fields rather than hectares. Area-weighted histograms would be similar.) The distribution is right skewed with most fields having values under 25 kg ha^{-1} Morgan’s P. There are some clearly outlying values above Kleinman *et al.'s* (1999) estimated saturation value of 35 ppm or 78 kg ha^{-1} Morgan's P.

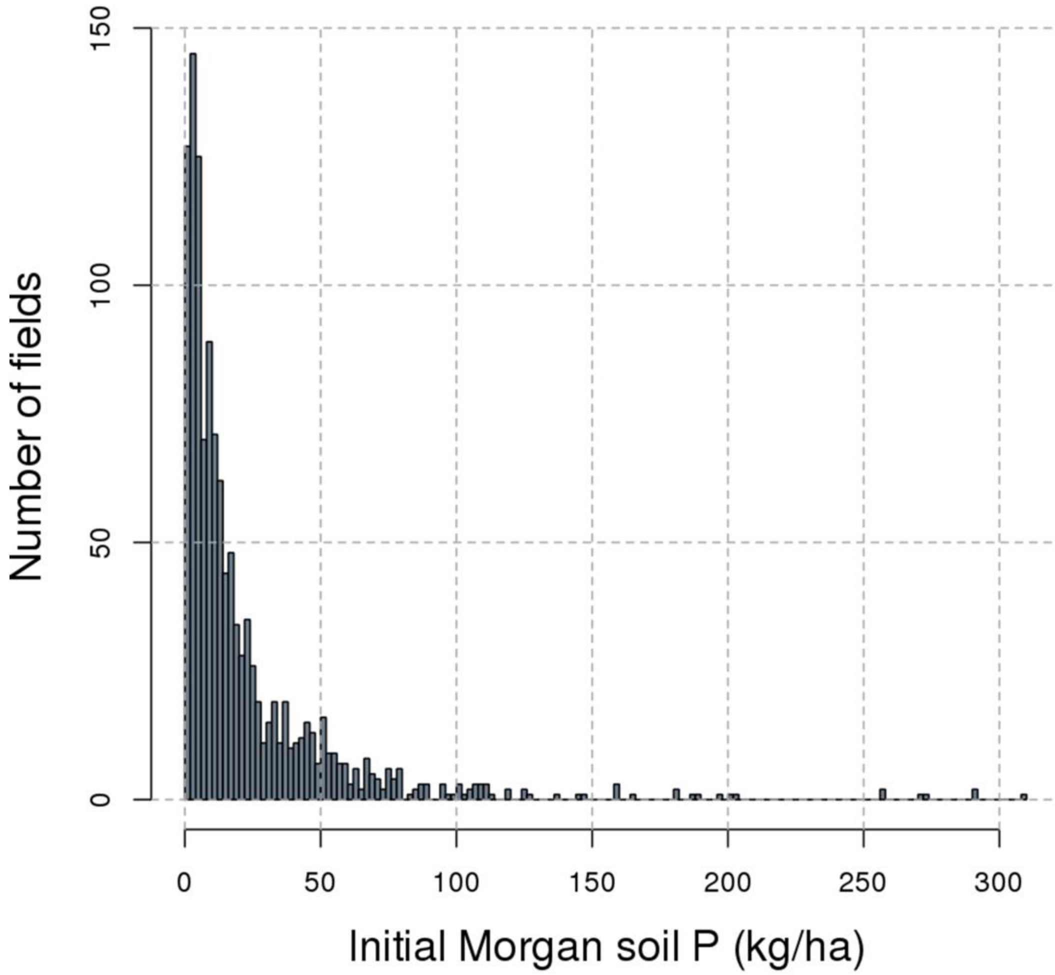

Figure 9: Variability of initial Morgan's soil P

Figure 10 replots the initial Morgan's P as a cumulative probability distribution instead of incremental, and superimposes the final Morgan's P distribution. These two distributions are indistinguishable. Part of the similarity is due to Morgan's P levels persisting over time -- final Morgan's P has a correlation of 0.69 with initial Morgan's P (see Table 7 near the end of this chapter).

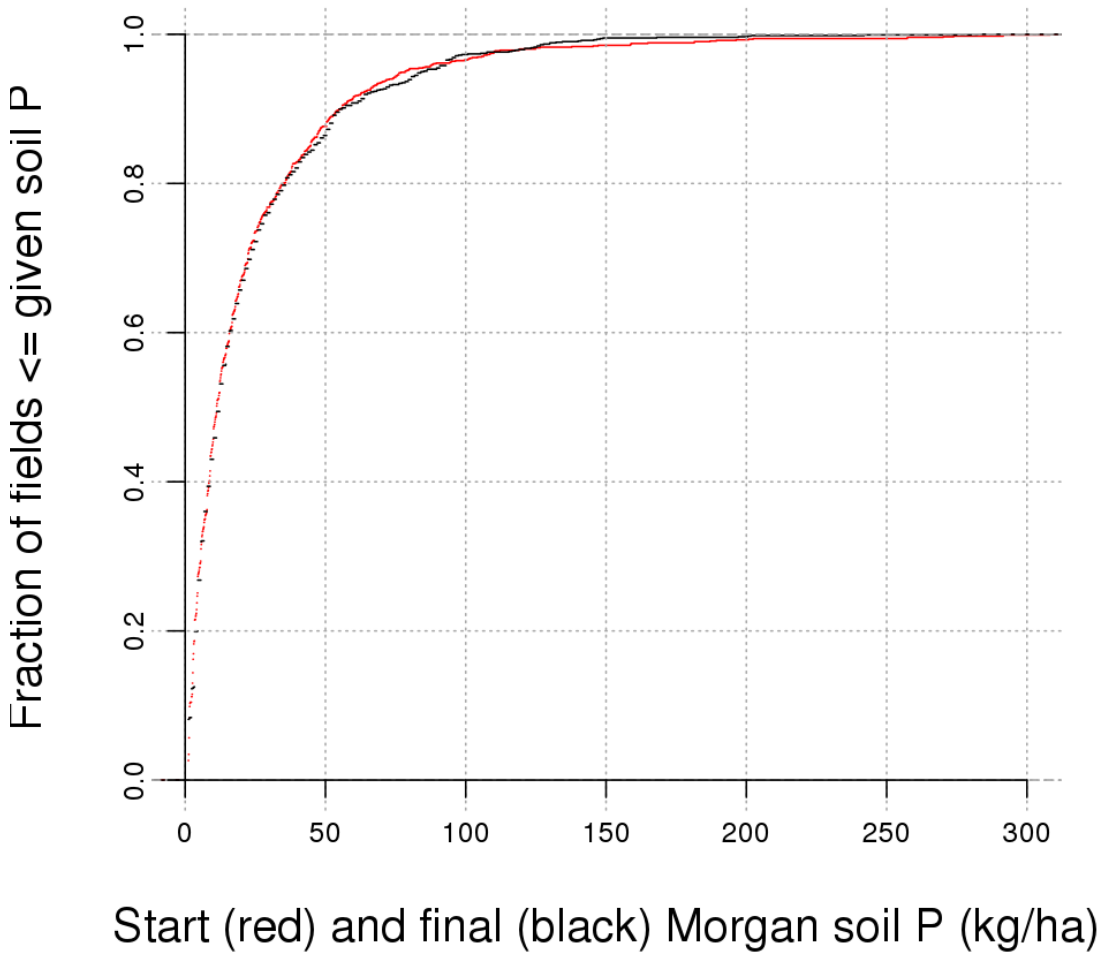

Figure 10: Cumulative probability distributions of initial and final Morgan's soil P

A paired Wilcoxon signed-rank test for the difference between last and first Morgan's P yields a 95% confidence interval of -0.27 to +1.12 kg ha^{-1}, indicating that *in aggregate there was no significant change in Morgan's P*. This is surprising in light of the mass balance surplus and the surrounding New York trend of increasing Morgan's P.

Figure 10 and the Wilcoxon test only show that there was no significant overall change; some fields could have gone up, and others down, offsetting one another. Figure 11 plots paired final versus initial Morgan's P. The diagonal line marks the boundary between decreasers and increasers: points to the upper left of the diagonal represent increased P fields, and points to the lower right represent decreased P fields. The figure's LOESS[§] curve tracks the vertical average (final Morgan's P) for a given horizontal point (initial Morgan's P). Its shape in relation to the diagonal indicates a *tendency for final Morgan's P to be higher than initial P for the lowest initial values, and final P lower than initial P for the higher initial values*. The breakpoint where the LOESS curve crosses the initial=final diagonal is around 12 kg ha^{-1}, near the10 kg ha^{-1} point where Cornell's soil test lab would no longer recommend adding P for field crop purposes (excepting starter mineral fertilizer for some crops). The increase in initially lower Morgan's P fields might be even higher were Morgan's extractant not leaving behind sorbed P.

[§] The 2D LOESS curves used in this document, for "Locally Weighted Scatterplot Smoothing" (proposed by Cleveland, (1979)), fit a series of low-degree, overlapping polynomials using weighted regression to a horizontally-moving vertical band of the scatterplot data. The weighting emphasizes the band center and deemphasizes edges. A zero degree polynomial would yield a center- weighted moving average. The polynomials used here are quadratics.

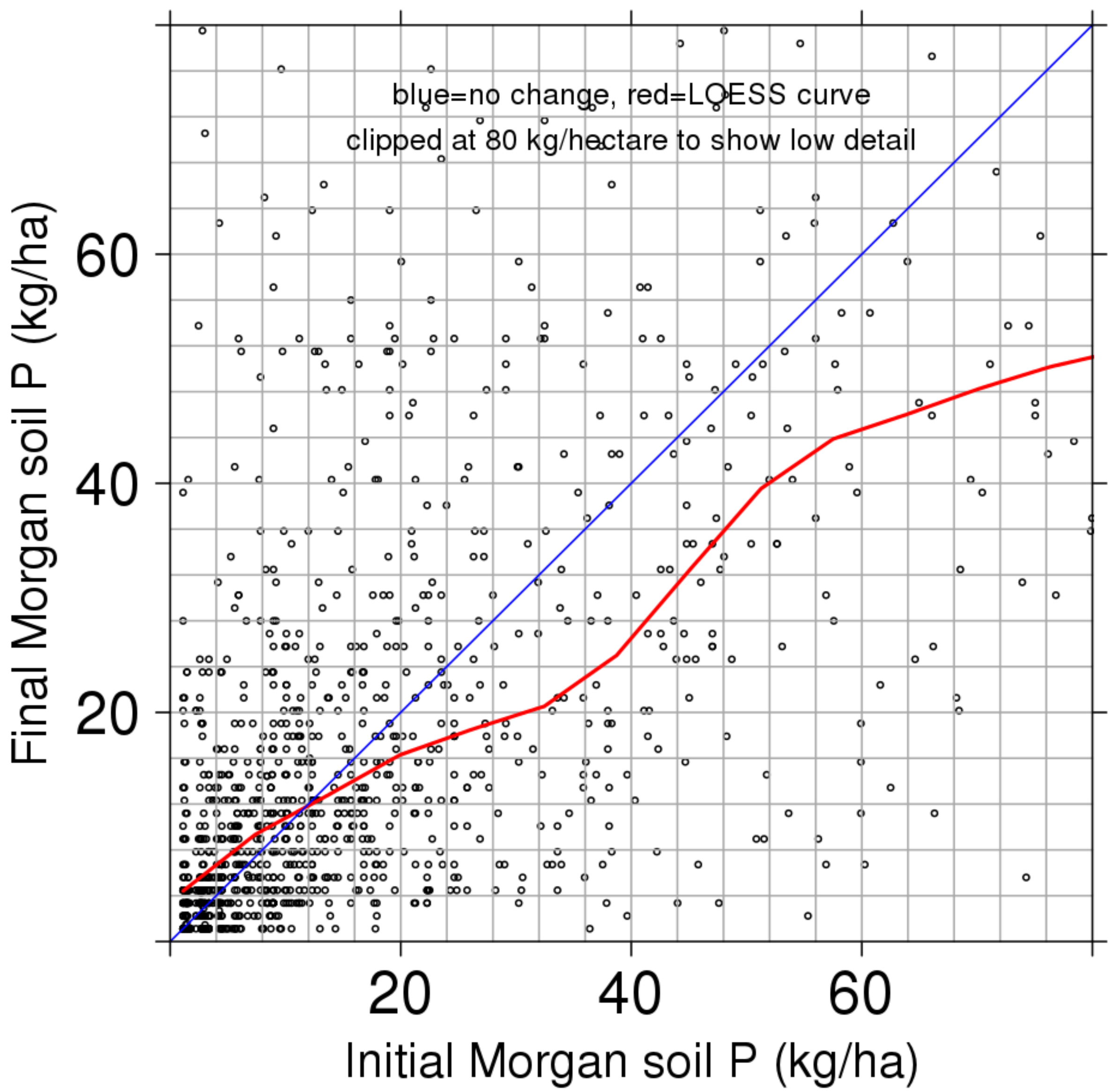

Figure 11: Initial versus final Morgan's soil P, field by field, with change tendency

Morgan's P change rates (kg ha^{-1} yr^{-1}) between the final and initial sample of the series are distributed almost symmetrically (Figure 12). The median and mean are slightly negative.

Similarly to Figure 11, Figure 13 indicates a correlation (within great noise) between the midpoint of a field's Morgan's P and the direction and magnitude of Morgan's P change. The LOESS curve is above zero from 0 to 15 kg ha^{-1}, crosses the zero line at 15, and is below zero from 15 to 30. The maximum rates of change are at 12 (gaining) and 24 (losing); overall the averaged changes are very small and could not be detected within this degree of scatter without tracking hundreds of fields.

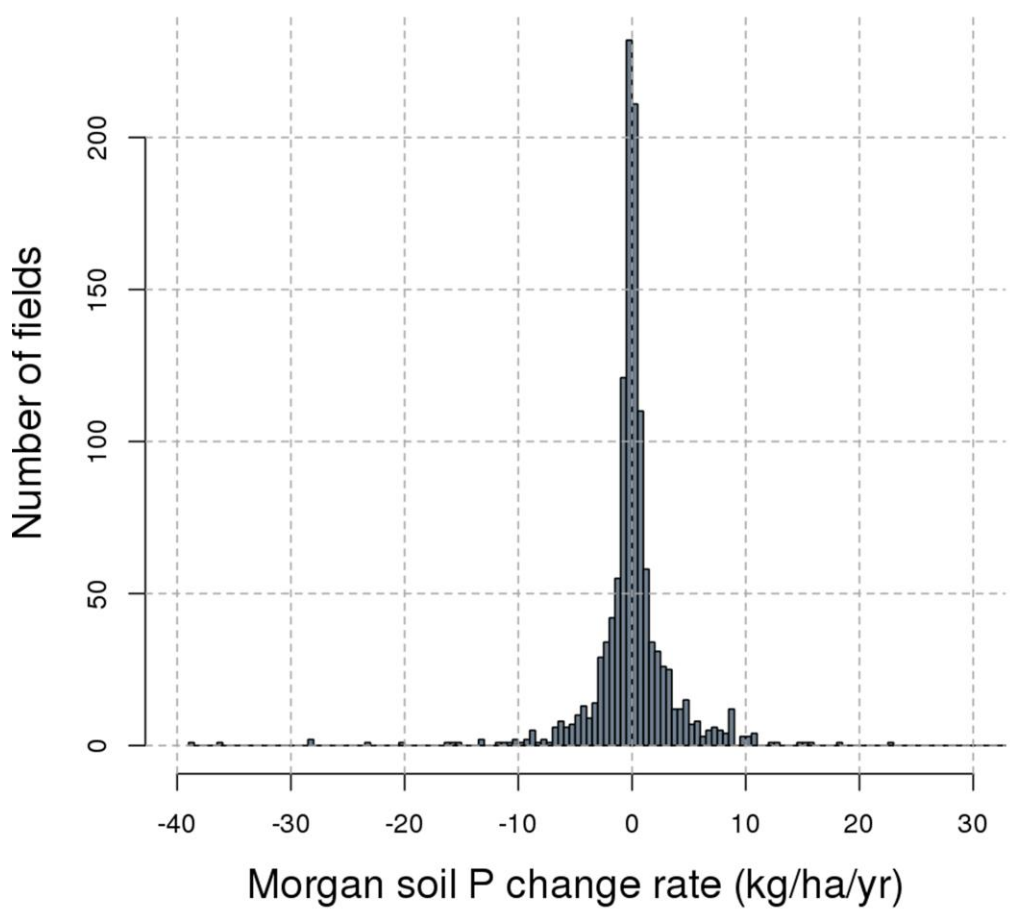

Figure 12: Frequency distribution of end-to-end rate of change in Morgan's soil P (ΔP/Δt)

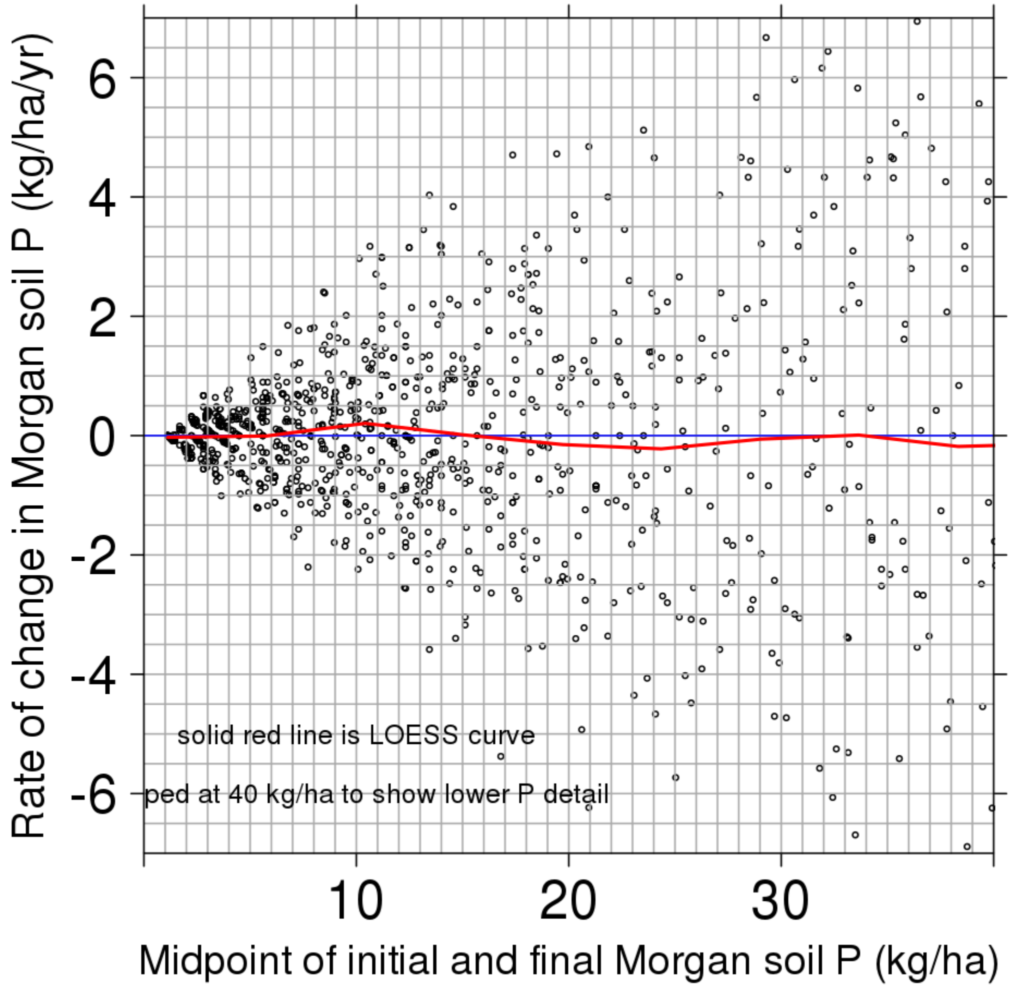

Figure 13: Relationship between rate of change of Morgan's soil P and P level

Consistent with the Wilcoxon test result, Figures 11-13 all imply the absence of any significant trend in soil test P over time on these long-tracked fields. As indicated in Chapter 2's discussion about mass balances, there should have been an accumulation of soil total phosphorus that arises from the farm gate admitting 2- to 3-times as much P in livestock feed (and to a lesser extent mineral fertilizer) as leaves in farm products. Total P should have been increasing by a few kg ha^{-1} $year^{-1}$, Morgan's P by less.

One probable explanation for not seeing the total soil P mass balance surplus show up as a Morgan’s P increase lies in the redistribution of manure implied by the LOESS lines in Figures 11 and 13. If the low fields are rising and the high fields are falling, that could indicate a change in manure use philosophy by the farms that WAP deliberately sought. A very high total P and Morgan's P beyond saturation can build up in a field that is a frequent default destination for manure. When manure must be spread every day due to lack of storage and labor or machinery limitations, and when access to distant fields is difficult due to deep snow or muddy soil, a default destination near to the livestock barn can be the only option. With many area barns near to watercourses -- a relic of when stream water was used for cooling milk (R. Weidenbach, personal communication) -- the near-barn accessible fields will also be in hydrologically sensitive areas. WAP's manure spreading advice has been to redirect away from these "old default" fields for pathogen as well as nutrient reasons. The advice becomes more feasible to implement when backed up with WAP-funded new spreading equipment, new storage arrangements, and information about the crop production shortcomings of leaving more distant fields without the nutrient benefit of manure. There was also community pressure specifically about phosphorus. Eutrophication concerns of New York City froze expansion of all four municipal wastewater treatment plants for several years in the Cannonsville basin (Delaware County Board of Supervisors, 1999). Farmers were on notice about the public scrutiny of their operations. They seem to have adjusted their behavior, despite the extra labor and complexity needed to follow their nutrient management plan.

The non-appearance of a significant Morgan's P increase must also be affected by the differential fate of added mobile P, depending on the initial Morgan's P conditions, that was cited in Chapter 2 in the discussion of the Finnish field experiments. The new destination fields with their low initial P would be favorable places to sorb P out of reach of runoff and the Morgan's extractant. Unlike the old default fields with their high P, the fields under 12 kg ha^{-1} have plenty of remaining capacity below Kleinman's estimated 78 kg ha^{-1} average saturation point for this region.

Associations Between Phosphorus Change and Field Attributes

Local farm fields occupy the broad West Branch Delaware River valley, tributary valleys, and uplands. The upland fields are considerably different in farming opportunities and constraints, very restricted compared to the more flexible and productive valley fields. Figure 14 illustrates that these types were also considerably different in their starting phosphorus values. The lowland fields have much higher initial Morgan's P values than upland fields, presumably because manure had been more frequently spread in lowlands. The lowland fields in the long-participating excerpt had higher Morgan's P despite more frequent saturation that could have washed away manure or leached excess P from soil, as indicated by higher theoretical soil topographic index values of lowlands (Figure 20). (Note that the soil topographic index numbers used in this document have higher values when soil is expected to saturate with water more frequently; the term "wetness" is carried along to emphasize this. Other reports use an index that is lowest for the most frequent saturation.)

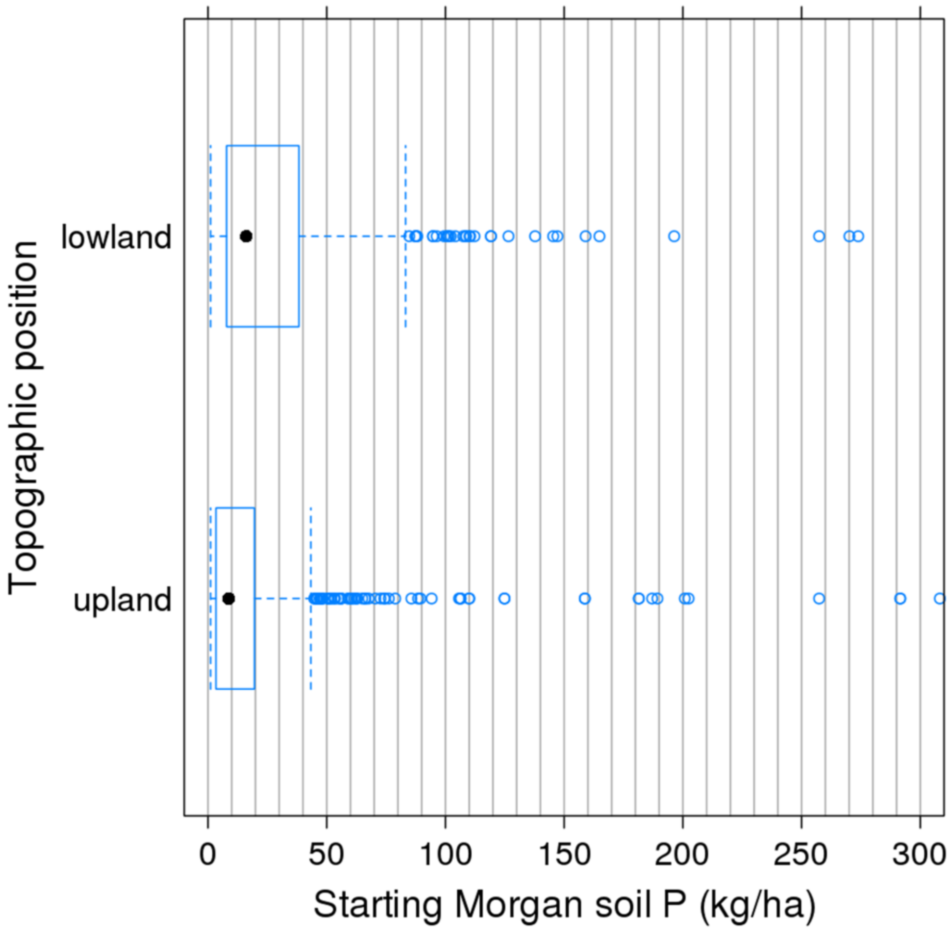

Figure 14: Initial Morgan's soil P versus topographic position (from temperature regime in USDA Soil Survey)

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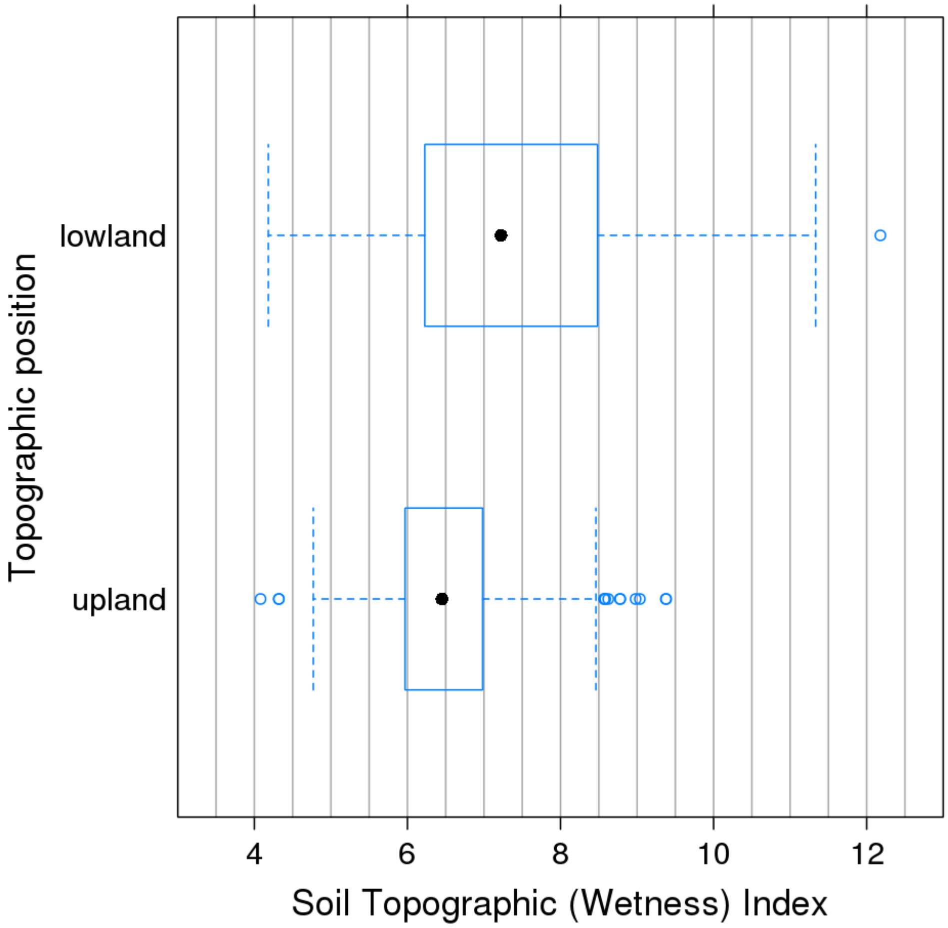

Figure 15: Topographic position versus potential wetness

Land having more corn years tends to be higher in phosphorus (Figure 16), perhaps due to somewhat more liberal manure application (Figure 17). Grass is more common in any given year, either in rotation with corn or grown in all years as a crop or in pasture. (Continuous grass is included in the leftmost boxplots in Figures 16 and 17.) Early 2000's whole basin water quality modellers in the area have assumed in calibration that corn has a much higher water quality impact than grass or pasture (New York City DEP, 2001; Tolson and Shoemaker, 2004).

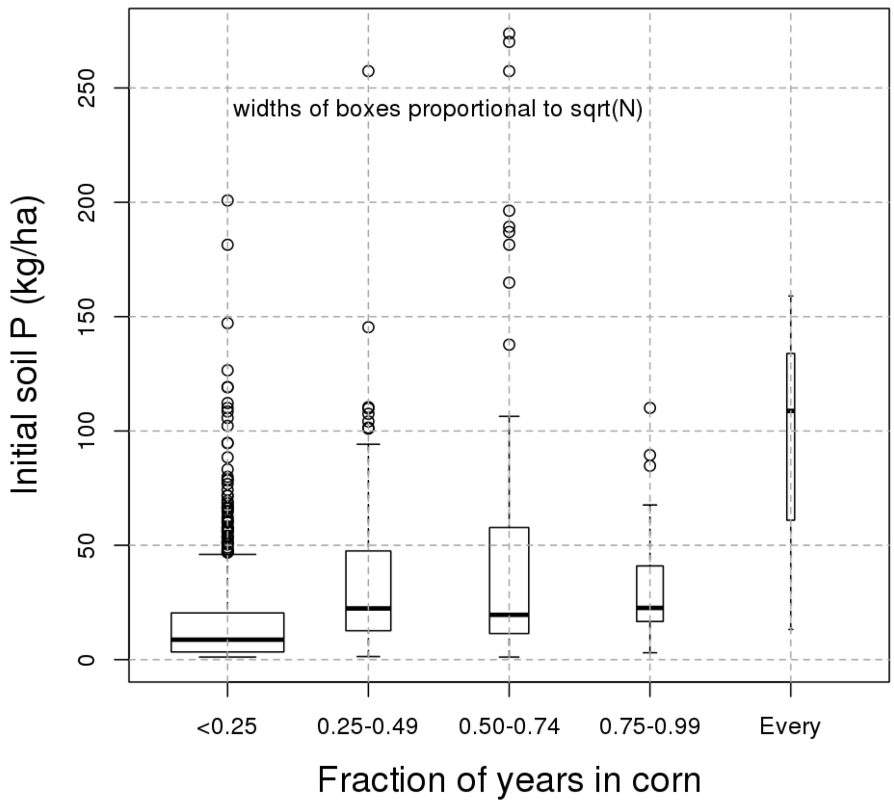

Figure 16: Corn frequency association with initial Morgan's soil P

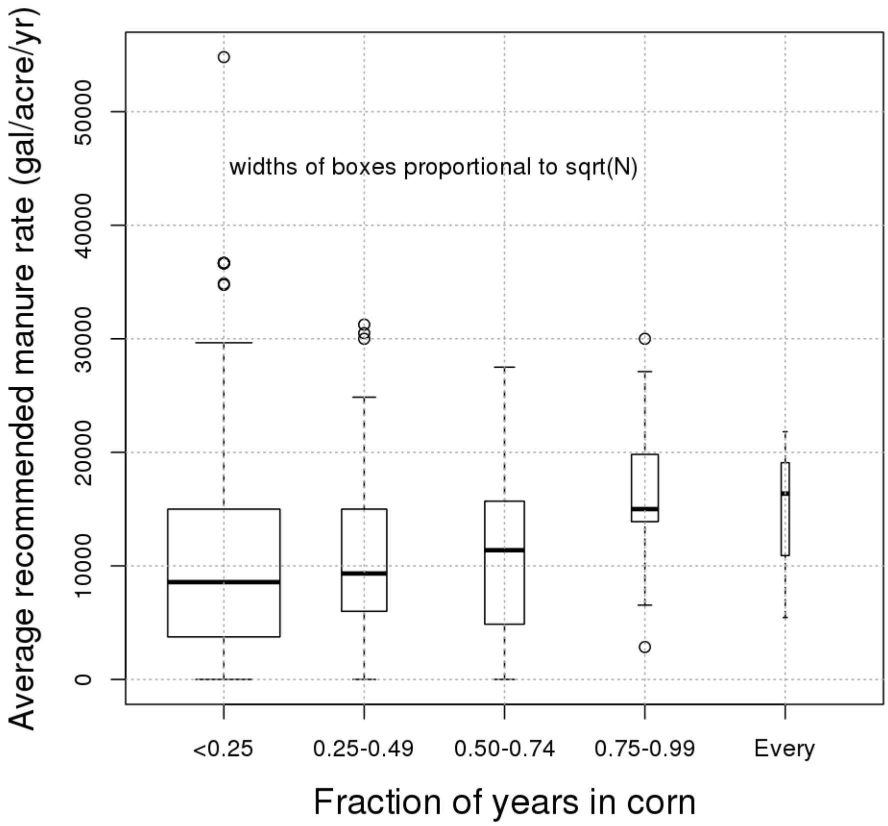

Figure 17: Corn association with manure recommendation

Correlations

Table 7 presents correlations among several candidate dependent and independent variables for regression analysis. A greater fraction of years in corn is associated with higher final soil P. Starting or final soil P are negatively correlated with extractable iron and aluminum, and positively correlated with extractable calcium. Soil iron and aluminum are positively correlated with one another, and each is negatively correlated with soil calcium. Somewhat surprisingly, the recommended manure rate is not strongly correlated with any other variable; one might expect it to be negatively correlated with initial Morgan's P -- however the nitrogen in manure is needed for most crop production.

Table 7: Correlations among field variables (all fields)

	P_i	**P_f**	**ΔP/Δt**	**Wetness**	**FrCorn**	**ManRecY**	**Ca**	**Fe**	**Al**
Symbol in regressions:				X_w	X_k	X_m	X_c	X_f	X_a
P_i		0.69	-0.44	0.18	0.36	-0.09	0.44	-0.28	-0.47
P_f	0.69		0.33	0.14	0.47	0.00	0.34	-0.26	-0.40
ΔP/Δt	-0.44	0.33		-0.08	0.11	0.11	-0.13	0.03	0.11
Wetness	0.18	0.14	-0.08		0.21	-0.00	-0.08	-0.03	-0.26
FrCorn	0.36	0.47	0.11	0.21		0.10	0.14	-0.27	-0.31
ManRecY	-0.09	0.00	0.11	-0.00	0.10		-0.01	-0.01	0.02
Ca	0.44	0.34	-0.13	-0.08	0.14	-0.01		-0.43	-0.53
Fe	-0.28	-0.26	0.03	-0.03	-0.27	-0.01	-0.43		0.72
Al	-0.47	-0.40	0.11	-0.26	-0.31	0.02	-0.53	0.72	

P_i = initial Morgan's soil P; P_f = final Morgan's soil P; ΔP/Δt = rate of change of Morgan's P;
Wetness = soil topographic (wetness) index; FrCorn = fraction of duration spent growing corn;
ManRecY = average annual manure recommendation rate (surrogate for unavailable actual manure use);
Ca, Fe, Al = calcium, iron, and aluminum as extracted by Morgan's procedure

The Morgan's phosphorus and other field data are very "noisy", and inter-correlations low, compared to data from controlled research settings like the cited Finnish examples. Despite this, the large number of field series will allow statistical techniques to be applied that prune away the edges of the "noise cloud" and focus on the centers of the data. The LOESS curves shown earlier in this chapter are one example of a technique that reduces noise by averaging over tens of nearby points and gives less weight to data far away from the center than to data near the center. The conclusions of (1) no overall Morgan's P change, and (2) evidence of manure redistribution toward low P fields, are robust because of the large data set and techniques less sensitive to outlying data such as the Wilcoxon test. The following chapter will focus on applying correlations to discover additional insights.

4. Statistical Models of Phosphorus Change

This section describes and interprets applications of conventional multiple linear regression and robust multiple linear regression that omits or de-emphasizes outlying cases. Field series that have incomplete data for any independent variable are omitted from all regressions, so that goodness of fit statistics may be compared across different regressions within a set. The regressions use the field database excerpt described in Chapter 3, specifically the subset of 747 data-complete cases and smaller selections from within the 747.

Regression Framework

The cross correlation Table 7 and exploratory regressions provided hints about which combinations of independent variables should be included in regression equations. In general, highly correlated independent variables were not used together in a regression. This led to omitting iron from the final regression analyses because of its high correlation (r=0.72) with aluminum and its similar influence to aluminum on phosphorus. Regressions using a dummy variable to represent upland versus lowland fields, and ones using the organic matter variable, did not yield additional insight and were set aside. Five independent variables representing different types of influence on Morgan's soil phosphorus remained: aluminum (model symbol a), calcium (c), corn (k), wetness index (w), and manure recommendation (m).

Table 8 defines the regression model notation using the narrowed independent variable set. The "base" model with zero variables is a vehicle to present the total standard error of the $\Delta P/\Delta t$ (rate of change of Morgan's soil P over time) dependent variable. The "kwcam" model includes all five candidate independent variables. All possible subsets of 0 to 5 variables were explored, a total of 32. For reference, Appendix A following Chapter 5 presents histograms of the five independent variables. Earlier Figure 12 showed the distribution of the dependent variable.

Table 8: Regression model notation

model "base"	$\Delta P / \Delta t = Y = \beta_0 + \epsilon$ (no independent variables, yields a standard error equal to standard deviation of $\Delta P/\Delta t$)
model "kwcam"	$\Delta P/\Delta t = Y = \beta_0 + \beta_k X_k + \beta_w X_w + \beta_c X_x + \beta_a X_a + \beta_m X_m + \epsilon$
	$\Delta P/\Delta t$ = rate of change in Morgan's extractable soil phosphorus, kg ha^{-1} yr^{-1} β_0 = intercept = value of $\Delta P/\Delta t$ when all independent variables are zero $\beta_k X_k$ regression coefficient and variable for fraction of years in **corn** $\beta_w X_w$ regression coefficient and variable for soil topographic (**wetness**) index $\beta_c X_c$ regression coefficient and variable for Morgan's extractable soil **calcium** (ppm) $\beta_a X_a$ regression coefficient and variable for Morgan's extractable soil **aluminum** (ppm) $\beta_m X_m$ regression coefficient and variable for recommended **manure** (gallons $acre^{-1}$ $year^{-1}$) ϵ regression residual term (error)
model "k" and the other 29	$\Delta P/\Delta t = Y = \beta_0 + \beta_k X_k + \epsilon$ and so forth for all combinations of k, w, c, a, m taken zero to five at a time, 32 models in total

A "conventional" regression here means a standard least squares regression in which all cases received equal weight in fitting. Models were fit with the *lm( )* function of the R-Project's statistical package (R-Project, 2009). "Robust" regressions employed the R-Project's *lmrob( )* function, which uses a fitting algorithm attributed to Yohai (Yohai et al, 1987; Macehler, 2009). *lmrob( )* does a candidate weighted regression, discovers an outlying case that has high influence (leverage) on results, then does another iteration with that outlying case set to have a weight smaller than 1.0 and possibly zero. Eventually convergence criteria are met and iteration terminates. For this data set, *lmrob( )*'s results were very similar to those found via an iterative manual approach of excluding cases that the conventional *lm( )* algorithm reported as having high leverage.

There were four sets of regressions. The first set used 674 of 747 complete field series records. The omissions had initial or final Morgan's phosphorus values higher than 75 kg ha^{-1} , thus could be high outliers which were evident in the plots of the previous chapter. This cutoff level is also near Kleinman's average phosphorus saturation estimate of 78 kg ha^{-1} Morgan's P for the geographic area's soils. A robust regression set was run for all 747 field series, reasoning that the algorithm would be better at excluding true outliers than using a fixed Morgan's P cutoff. A third set, conventional in fitting, focused on fields that included at least one year of corn within their history and Morgan's P <= 75 (N=228). The fourth set also focused on corn and used robust fitting without excluding the high P outliers. Appendix B presents results of all regressions in all sets, including two more sets of conventional regressions done without excluding high P outliers.

Table 9 provides background for interpreting the signs of the regression coefficients. The effect of Morgan's extractable calcium is less certain than the other effects.

Table 9: Expected directional influences of independent variables

Independent Variable	**Positive Coefficient Meaning**	**Expected Sign**
X_k corn	more corn in rotation increases Morgan's P accumulation	Positive: more manure or mineral fertilizer applied
X_w potential wetness	wetter soil position (i.e. more frequent saturation) increases Morgan's P accumulation	Negative: washout by wetter conditions
X_c calcium	higher extractable calcium increases Morgan's P accumulation	Variable? Soil pH tends to be low so few insoluble precipitates would be formed (negative coefficient).
X_a aluminum	higher extractable aluminum increases Morgan's P accumulation	Positive: retains against washout, but can release back to solution
X_m recommended manure	higher manure recommended increases Morgan's P accumulation	Positive: more manure applied

Regressions for All Crops

Table 10 presents selected results from the 32 candidate models in regression set 1. The selection includes only models having all variables' coefficients significantly different from zero at the $p<0.05$ level. While the high N=674 values made many of the 32 regressions highly significant under an F test ($p<<0.01$), the scatter evident from the earlier graphical presentations is still dominant and most variation of Morgan's P change cannot be accounted for by the available independent variables. Dependent and independent variables could be noisy themselves, and other factors could be influential. The best model, via lowest standard error or highest adjusted R^2, was "kam", in which corn (X_k), aluminum (X_a), and manure (X_m) have coefficients significantly different from zero (all p<0.001 except manure p<0.01). Across the various listed models, corn has a positive coefficient, wetness index negative, calcium negative, aluminum positive, and manure positive. These have signs consistent with the expected ones in Table 9.

Table 10: Fits of better regression models, all crops, omitting values over 75 kg ha^{-1} initial or final Morgan's P (N=674)

Model	stderr	Adj R^2 %	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
	1.93		0.052					
ka	1.89	3.8	-0.646	1.213***			0.416***	
am	1.89	4.0	-0.746				0.339***	0.317***
kwm	1.90	2.8	0.610	0.848*	-0.144*			0.295***
kam	1.88	5.2	-0.937	1.091**			0.407***	0.288**
wcm	1.90	2.7	1.102		-0.130*	-0.185*		0.320***
kwcm	1.90	3.5	1.291	0.896*	-0.164**	-0.198*		0.297***

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

Figure 18 uses the best "kam" equation

$$\text{predicted } P_f = \text{observed } P_i + (-0.937 + 1.091 {*} X_k + 0.407\text{x}10^{-2} {*} X_a + 0.288\text{x}10^{-5} {*} X_m) * \Delta t$$

to create predicted final Morgan's P values. The red points plot these against the P_i values, superimposed on a background of the earlier Figure 11 using black dots. The LOESS curve follows the trend of the predicted phosphorus values for given initial Morgan's P. As in Figure 11, the LOESS curve is above the diagonal at low initial Morgan's P values, indicating a tendency for phosphorus to increase with time. It crosses around 12-16, then falls below the diagonal above 16 indicating a tendency for Morgan's P to decrease with time. The regression does not explain much of the total variance of the rate of phosphorus change, thus the band of red dots is narrower around the diagonal than the cloud of black observed points in the background.

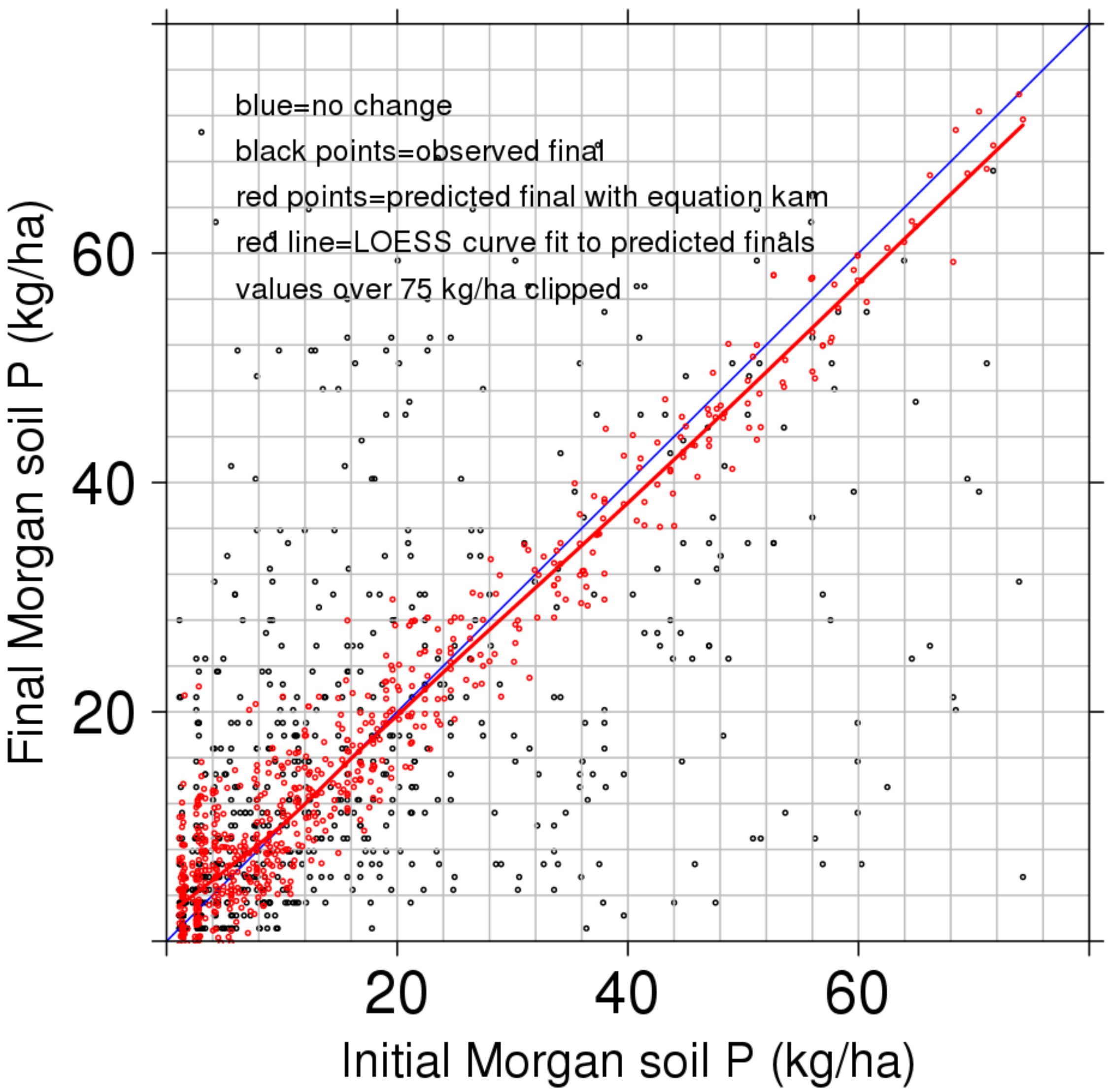

Figure 18: Observed and predicted final Morgan soil P (all crops, N=674)

The robust model results for all crops, in Table 11, include similar coefficient sign results with a lower standard error, 1.2 kg ha^{-1} yr^{-1} versus around 2.0 for conventional regressions. Manure has a more precise coefficient ($p<0.001$) in the algorithmically narrowed data set than in the conventional regression set, and the coefficients of corn and calcium are not significantly different from zero ($p>0.05$) thus no rows including them are included in the table. While the robust models do not yield additional insights, they indicate that the semi-arbitrary exclusion of fields with high phosphorus values from conventional regressions did not yield a very different result from selective exclusion using individual point leverage.

Table 11: Fits of better robust regression models, all crops (N=746 before removing outliers)

Model	outliers weighted 0.0	RRSE	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	54	1.26	0.055					
rob-w	52	1.26	0.853		-0.118*			
rob-a	51	1.25	-0.384				0.287***	
rob-m	55	1.25	-0.160					0.201***
rob-am	54	1.24	-0.587				0.284***	0.194***

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

RRSE = robust residual standard error of the regression, equivalent to standard error in conventional regression but using algorithmically determined weights (Croux et al.*, 2003).*

Regressions for Fields Including Corn in Rotation

When the data set is narrowed to fields including at least one year of corn, goodnesses of fit shown in Table 12 improve to adjusted R^2 values of up to 10.5%, but the standard errors around

2.3 are higher than in the all-crops regressions. Coefficient signs are the same as in the all-crops regressions except for calcium flipping from negative to positive. Manure and aluminum also have less precise coefficient estimates. Figure 19's plot of predicted final P, using Model "kcam", versus observed initial P in has an even more pronounced "low initial P rises" LOESS curve tail in the lower left corner of the plot.

Table 12: Fits of better regression models, corn in rotations, omitting values over 75 kg ha^{-1} initial or final Morgan's P (N=228)

Model	stderr	Adj R^2 %	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	2.39		0.066					
k	2.35	3.3	-0.676	2.051**				
a	2.36	3.0	-0.552				0.639**	
m	2.34	4.1	-0.760					0.721**
ka	2.31	6.8	-1.399	2.203**			0.691**	
km	2.32	5.8	-1.193	1.594*				0.596**
ca	2.34	4.3	-1.916			0.411*	0.840***	
am	2.31	6.7	-1.316				0.607**	0.694**
kca	2.29	8.6	-2.944	2.303***		0.454*	0.914***	
kam	2.28	8.9	-1.841	1.771*			0.655**	0.552*
cam	2.29	8.0	-2.625			0.398*	0.801**	0.684**
kcam	2.26	10.5	-3.308	1.882**		0.436*	0.871***	0.533*

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

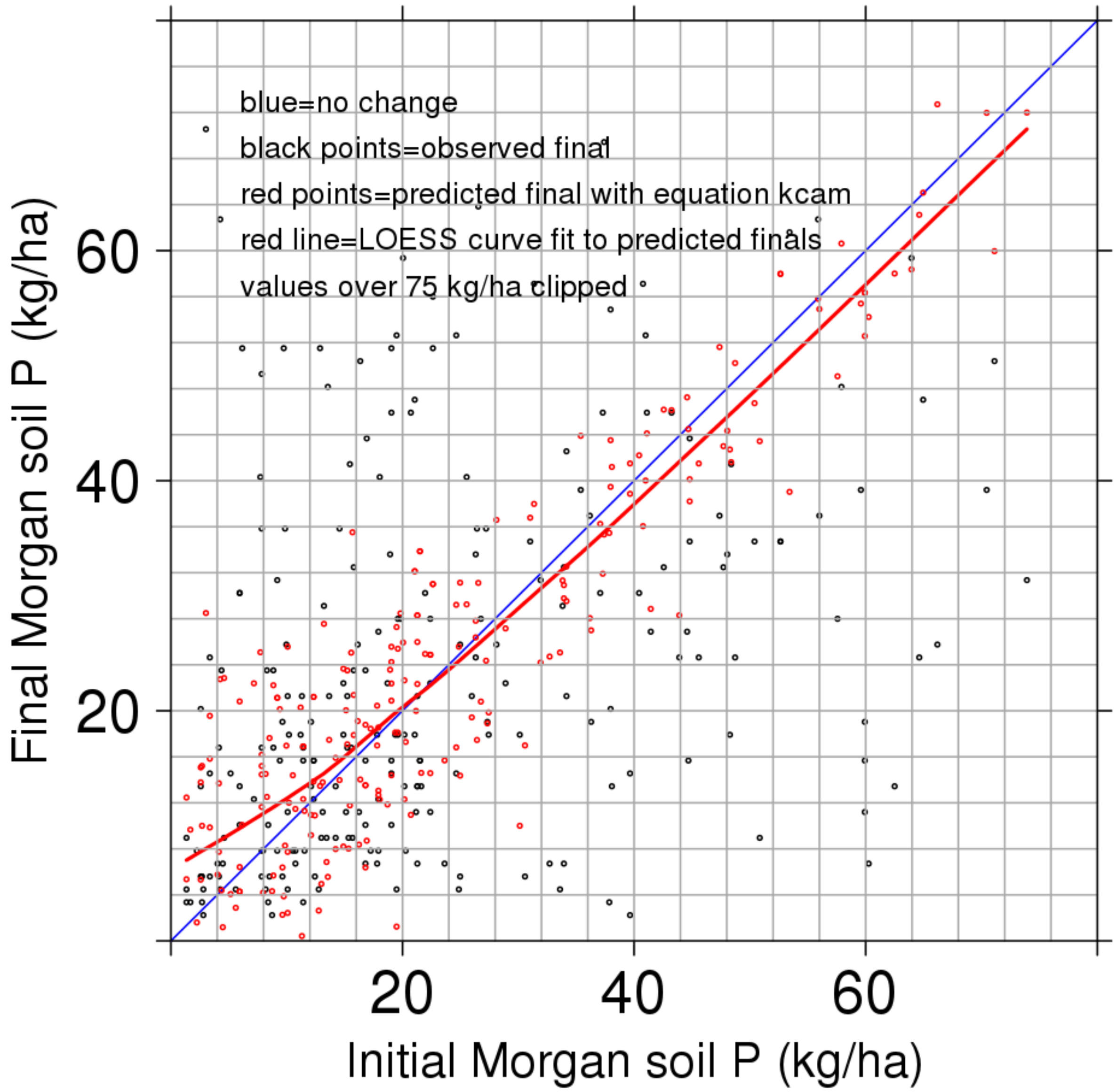

Figure 19: Predicted and observed final Morgan soil P (fields with corn)

Table 13's robust fitting results for the fields including corn again corroborates the analogous conventional fits. Corn and calcium reappear with coefficients significantly different from zero. Coefficient signs are consistent with the conventionally fitted coefficient signs.

Table 13: Robust regressions corn (N=285 before removing outliers)

Model	outliers weighted 0.0	rrse	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	9	2.48	0.113					
rob-k	9	2.49	-0.65	2.150*				
rob-a	9	2.44	-0.355				0.470*	
rob-m	9	2.48	-0.494					0.546*
rob-kw	9	2.47	1.247	2.370*	-0.274*			
rob-ka	9	2.46	-1.309	2.383*			0.577**	
rob-ca	10	2.43	-2.527			0.668*	0.794***	
rob-am	11	2.44	-0.938				0.461*	0.531*
rob-kca	10	2.44	-3.713	2.493**		0.722**	0.931***	
rob-cam	11	2.43	-3.197			0.682**	0.796***	0.557*

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

RRSE = robust residual standard error of the regression, equivalent to standard error in conventional regression but using algorithmically determined weights.

Summary of Groups of Regression Results

Table 14 brings together essential outcomes of the best fitting models of four groups of regressions. Except for calcium, the coefficient signs are consistently consistent with the expected signs from Table 9. Since none of the regressions explains very much of the total variance in the rate of change of Morgan's P, the equations are ultimately of little help toward management or modeling. They have primarily qualitative value.

Table 14: Overview of regression group results

Model group	**N**	**Base stderr**	**Best stderr**	**Corn signs**	**Wetness signs**	**Calcium signs**	**Aluminum signs**	**Manure signs**
All crop, P<=75	674	1.93	1.88	+	-	-	+	+
All crop, all P, robust	747 - outliers	1.26	1.24	(not sig.)	-	(not sig.)	+	+
Corn, P <=75	228	2.39	2.26	+	(not sig.)	+	+	+
Corn, all P, robust	285 - outliers	2.48	2.43	+	-	+	+	+

5. Discussion and Conclusions

1. *The WAP farm nutrient management data are very noisy.* Agricultural field level nutrient data have a coarse level of precision. Some of the coarseness arises from sampling of soil chemistry based on composited soil cores that may represent several acres of uneven wetness, multiple soil types, and uneven manure spreading. Agronomic uses of the data are designed around the coarseness.

Fortunately there are over 1200 field time series that can be employed to search for the anticipated effects of management. Patterns may be found among the central mass of data, particularly if outliers are identified and discounted.

2. *On average, Morgan's soil P was unexpectedly flat over time in the tracked WAP farm fields. The flat trend on average is composed of some fields rising offset by some fields falling.*

On average across over 1200 fields having at least six years of history, Morgan's P was flat between when farms joined the program and the most recent samples as of 2007. This is despite evidence in favor of increasing total soil P due to a persisting farm gate mass balance surplus, and a preceding 1981-2001 trend of increasing Morgan's P in New York State farm soils overall.

The initially low Morgan's P fields had a greater tendency to rise than fall, and the initially high fields had a greater tendency to fall than rise. This result would be consistent with the farmers' shifting excess manure away from traditional favorite fields and toward a wider variety of fields.

The flat trend would be consistent with the initially low P fields sequestering added phosphorus from Morgan's extractant, due to sorption on soil iron and aluminum.

3. *Multiple regression including outlier exclusion found empirical results consistent with theory, regarding which attributes of fields and their management influence the direction and magnitude of Morgan's P change.*

Coefficient signs from regression analysis indicate that corn frequency, manure rates (as recommended), and Morgan's extracted aluminum favor increasing Morgan's P, and soil topographic indices increasing with wetness favor decreasing Morgan's P. These align with expected directions of influence. These effects are faint within the large data set, though significantly different from zero. They would not be detectable in a smaller data set with fewer fields and shorter records.

The answer to this study's title question is Yes, soil test phosphorus can be used to detect trends in response to water-related nutrient management, *given a sufficiently large data set to overcome noise*, and *given interpretive techniques like LOESS fitting and robust regression* that are not too affected by imprecise data. This effort required hundreds of fields, persistence of at least six years, and extensive data conversion effort beyond that needed for nutrient management planning. It would have been helpful to have an additional phosphorus extractant besides Morgan's that yields sorbed P as well as P in solution, in order to test the speculation that the mass balance surplus is now being accumulated in the form of sorbed P, which is not detected using Morgan's extractant.

Appendix A: Histograms of Independent Variables Used in Regressions

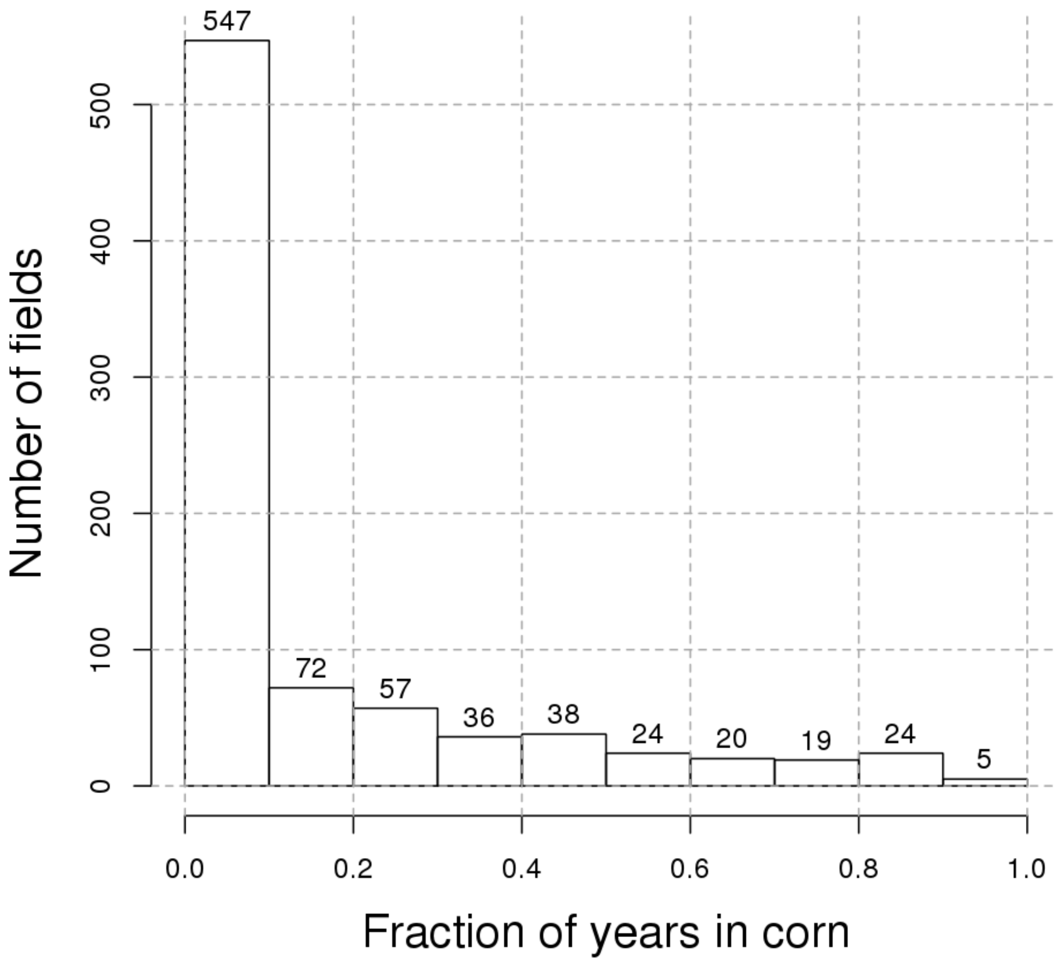

Figure 20: Histogram of corn years as a fraction of sampled duration

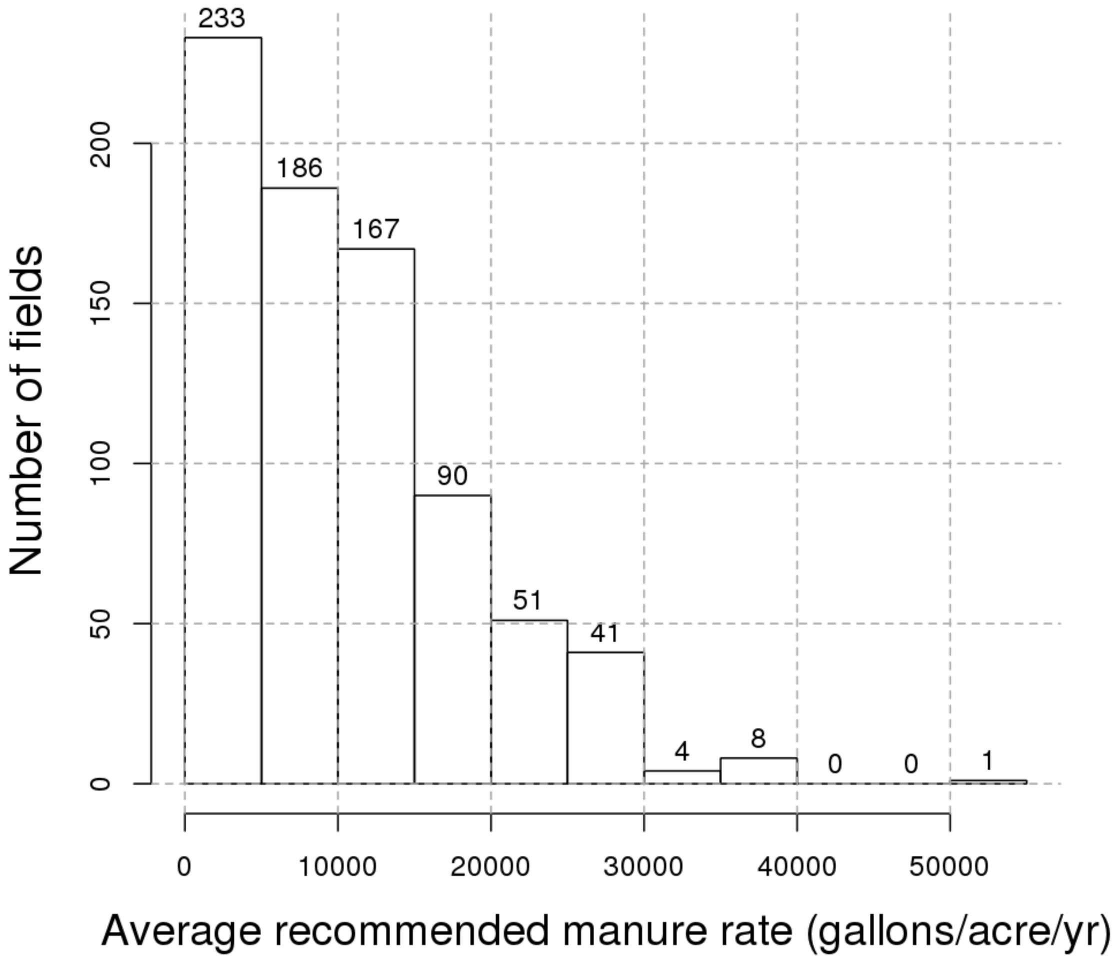

Figure 21: Histogram of average manure recommendation

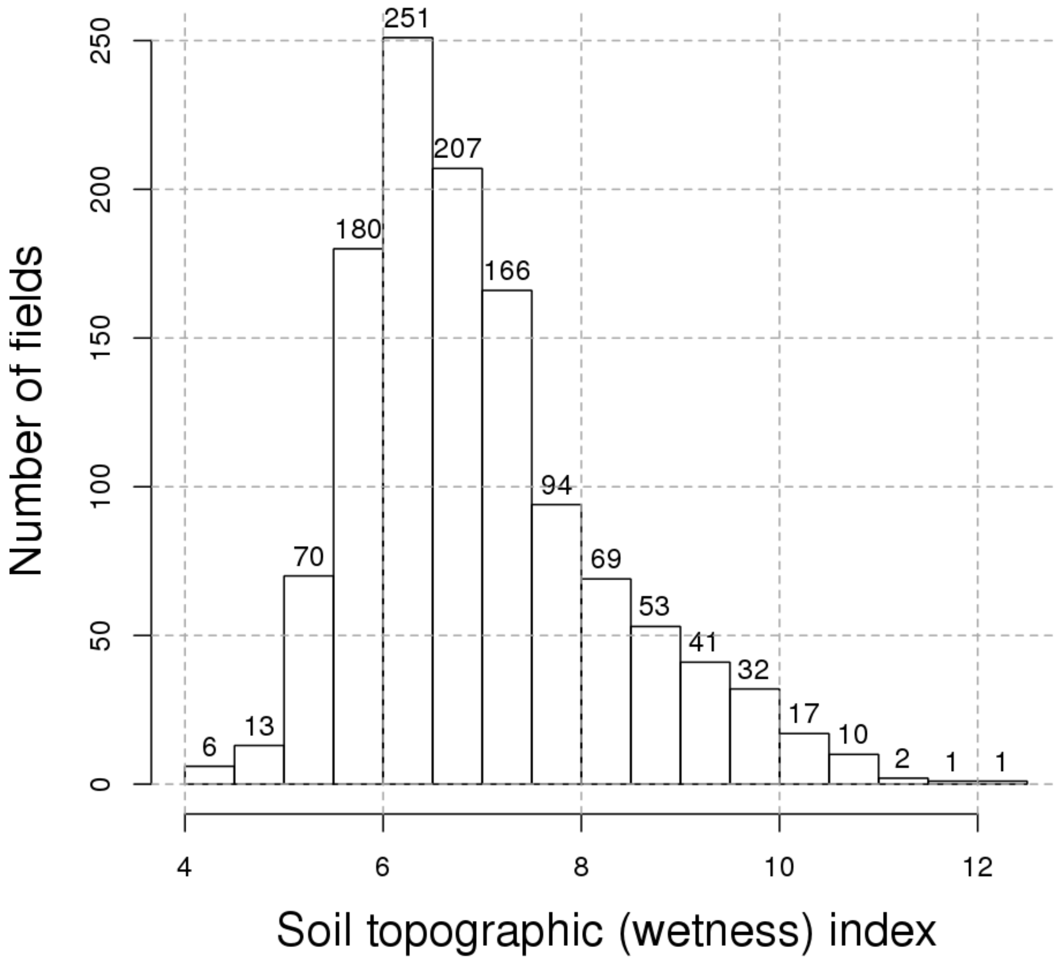

Figure 22: Histogram of soil topographic (wetness) index

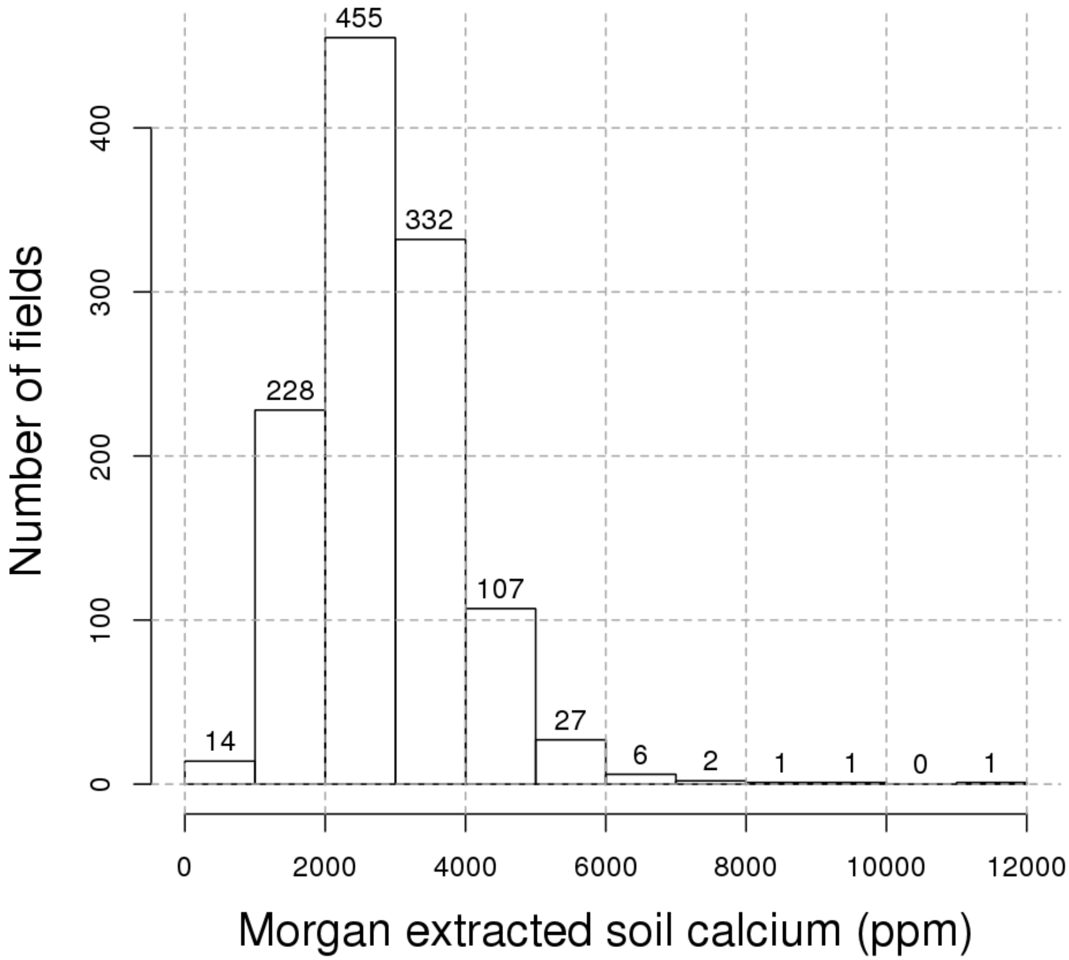

Figure 23: Histogram of extracted soil calcium

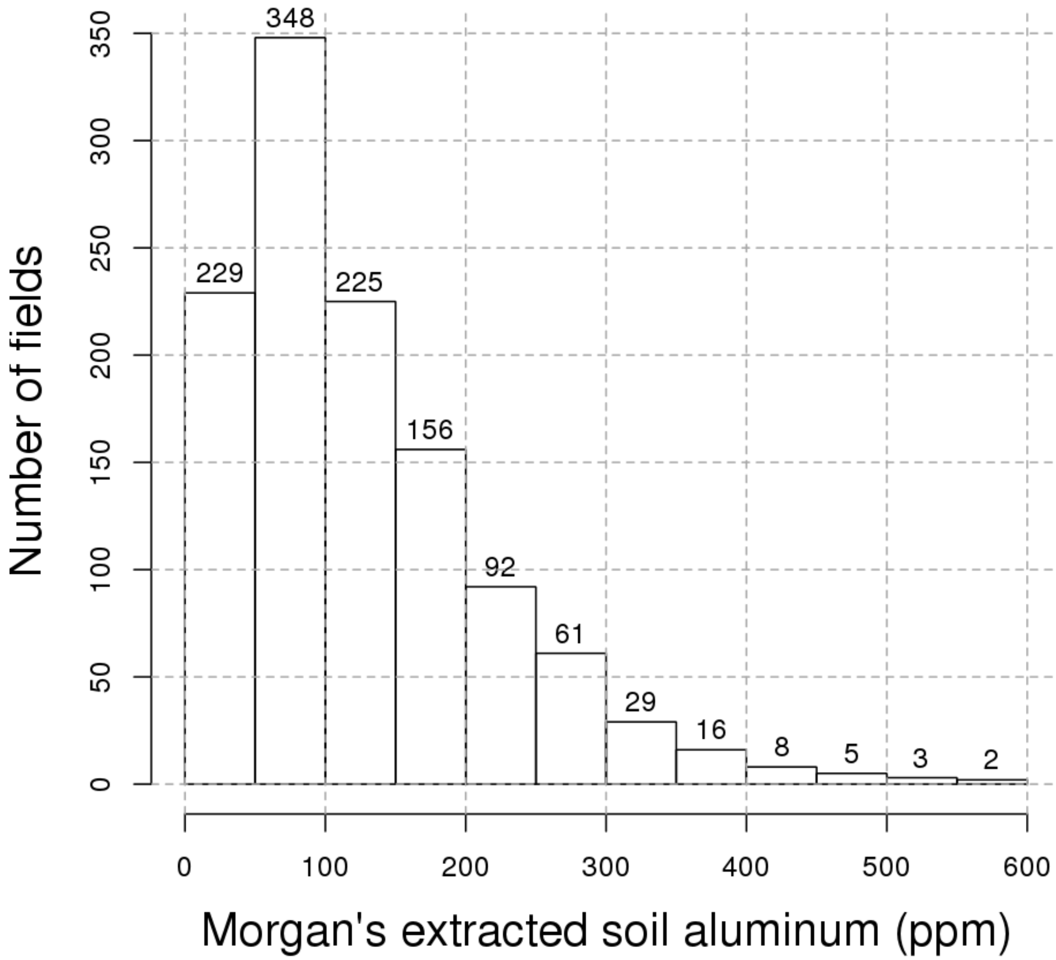

Figure 24: Histogram of extracted soil aluminum

Appendix B: All Regressions

Table 15: Fits of regression models, all crops, all Morgan's P levels (N=747)

Model	df	stderr	Adj R^2 %	F	pvalue	intercept	corn (c)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
	746	3.21				0.071					
k	745	3.19	1.2	9.895	0.0017	-0.156	1.516**				
w	745	3.21	0.5	4.749	0.0296	1.485		-0.204*			
c	745	3.19	1.6	13.41	0.0003	1.349			-0.443***		
a	745	3.20	1.1	9.076	0.0027	-0.428				0.403**	
m	745	3.20	1.0	8.72	0.0033	-0.382					0.417**
kw	744	3.18	2.2	9.22	0.0001	1.711	1.807***	-0.276**			
kc	744	3.16	3.3	13.76	1.356E-06	1.26	1.793***		-0.505***		
ka	744	3.16	3.4	13.95	1.127E-06	-0.976	2.158***			0.586***	
km	744	3.18	2.0	8.565	0.0002	-0.547	1.391**				0.378**
wc	744	3.18	2.3	9.916	0.0001	3.044		-0.235*	-0.469***		
wa	744	3.19	1.2	5.613	0.0038	0.614		-0.141		0.351*	
wm	744	3.19	1.5	6.763	0.0012	1.028		-0.204*			0.416**
ca	744	3.19	1.7	7.507	0.0006	0.825			-0.347*	0.199	
cm	744	3.17	2.6	11.11	0.0000	0.892			-0.440***		0.412**
am	744	3.18	2.1	8.806	0.0002	-0.861				0.395**	0.408**
kwc	743	3.14	4.7	13.28	1.885E-08	3.598	2.163***	-0.326***	-0.553***		
kwa	743	3.15	3.8	10.8	5.912E-07	0.475	2.303***	-0.202*		0.524***	
kwm	743	3.17	2.9	8.484	0.0000	1.291	1.679***	-0.270**			0.368**
kca	743	3.15	3.9	11.15	3.646E-07	0.219	2.123***		-0.328*	0.389*	
kcm	743	3.15	4.1	11.51	2.197E-07	0.863	1.668***		-0.498***		0.365**
kam	743	3.15	4.0	11.42	2.513E-07	-1.31	2.024***			0.568***	0.347*
wca	743	3.18	2.2	6.654	0.0002	2.769		-0.221*	-0.435**	0.066	
wcm	743	3.16	3.3	9.572	3.309E-06	2.582		-0.234*	-0.465***		0.411**
wam	743	3.18	2.2	6.606	0.0002	0.185		-0.142		0.343*	0.409**
cam	743	3.17	2.7	7.901	0.0000	0.395			-0.348*	0.190	0.409**
kwca	742	3.14	4.8	10.45	3.058E-08	2.652	2.313***	-0.282**	-0.440**	0.236	
kwcm	742	3.13	5.4	11.64	3.563E-09	3.169	2.036***	-0.320***	-0.546***		0.352*
kwam	742	3.14	4.4	9.673	1.251E-07	0.123	2.168***	-0.199*		0.507***	0.344*
kcam	742	3.14	4.6	9.989	7.064E-08	-0.109	1.987***		-0.330*	0.370*	0.349*
wcam	742	3.16	3.2	7.199	0.0000	2.347		-0.222*	-0.437**	0.057	0.410**
kwcam	741	3.12	5.5	9.653	6.087E-09	2.304	2.178***	-0.279**	-0.441**	0.218	0.345*

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

Table 16: Fits of regression models, all crops, omitting values over 75 kg/ha initial or final Morgan's P (N=674)

Model	df	stderr	Adj R^2 %	F	pvalue	intercept	corn (c)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	673	1.93				0.052					
k	672	1.92	0.6	5.265	0.02207	-0.045	0.790*				
w	672	1.93	0.4	3.568	0.05933	0.834		-0.114			
c	672	1.93	0.3	3.355	0.06743	0.486			-0.156		
a	672	1.91	2.2	16.43	0.00006	-0.398				0.341***	
m	672	1.91	1.8	13.02	0.00033	-0.299					0.319***
kw	671	1.92	1.4	5.633	0.00375	0.962	0.972**	-0.150*			
kc	671	1.92	1.0	4.468	0.01181	0.404	0.810*		-0.162		
ka	671	1.89	3.8	14.37	7.769E-07	-0.646	1.213***			0.416***	
km	671	1.91	2.2	8.445	0.00024	-0.362	0.671				0.301***
wc	671	1.92	0.9	4.004	0.01868	1.449		-0.131*	-0.180*		
wa	671	1.91	2.2	8.725	0.00018	0.052		-0.062		0.321***	
wm	671	1.91	2.1	8.298	0.00028	0.473		-0.112			0.317***
ca	671	1.91	2.1	8.268	0.00028	-0.52			0.035	0.359***	
cm	671	1.91	2.1	8.358	0.00026	0.146			-0.161		0.321***
am	671	1.89	4.0	14.95	4.427E-07	-0.746				0.339***	0.317***
kwc	670	1.91	2.0	5.524	0.00095	1.636	1.020**	-0.170**	-0.195*		
kwa	670	1.89	4.0	10.46	9.836E-07	0.057	1.307***	-0.099		0.390***	
kwm	670	1.90	2.8	7.524	0.00006	0.61	0.848*	-0.144*			0.295***
kca	670	1.89	3.8	9.781	2.541E-06	-0.926	1.248***		0.079	0.459***	
kcm	670	1.91	2.6	6.952	0.00013	0.095	0.691*		-0.166*		0.303***
kam	670	1.88	5.2	13.35	1.8E-08	-0.937	1.091**			0.407***	0.288**
wca	670	1.91	2.1	5.808	0.00064	0.028		-0.061	0.005	0.324**	
wcm	670	1.90	2.7	7.148	0.00010	1.102		-0.130*	-0.185*		0.320***
wam	670	1.89	4.0	10.3	1.238E-06	-0.305		-0.06		0.320***	0.316***
cam	670	1.89	3.8	9.98	1.925E-06	-0.839			0.027	0.354***	0.316***
kwca	669	1.89	3.9	7.865	3.379E-06	-0.113	1.316***	-0.093	0.035	0.411***	
kwcm	669	1.90	3.5	7.048	0.00001	1.291	0.896*	-0.164**	-0.198*		0.297***
kwam	669	1.88	5.4	10.63	2.368E-08	-0.265	1.181***	-0.094		0.382***	0.285**
kcam	669	1.88	5.1	10.12	5.891E-08	-1.173	1.121**		0.067	0.444***	0.286**
wcam	669	1.89	3.8	7.712	0.00000	-0.289		-0.061	-0.003	0.318**	0.316***
kwcam	668	1.88	5.3	8.499	8.19E-08	-0.384	1.188***	-0.09	0.025	0.397***	0.284**

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

Table 17: Fits of regression models, corn, all phosphorus levels (N=285)

Model	df	stderr	Adj R^2 %	fstat	pvalue	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	284	4.44				0.158					
k	283	4.38	3.1	9.981	0.0018	-1.158	3.360**				
w	283	4.41	1.6	5.524	0.0195	3.385		-0.446*			
c	283	4.43	0.6	2.642	0.1052	1.422			-0.414		
a	283	4.41	1.8	5.223	0.0230	-0.617				0.901*	
m	283	4.41	1.5	5.275	0.0224	-0.783					0.839*
kw	282	4.33	5.3	8.919	0.0002	2.458	3.679***	-0.517**			
kc	282	4.36	3.9	6.835	0.0013	0.236	3.511**		-0.476		
ka	282	4.32	5.3	8.99	0.0002	-2.247	3.757***			1.086**	
km	282	4.36	3.7	6.472	0.0018	-1.713	2.977**				0.628
wc	282	4.38	2.7	4.884	0.0082	5.428		-0.508**	-0.522*		
wa	282	4.39	2.3	4.352	0.0138	2.156		-0.361		0.717	
wm	282	4.38	3.0	5.415	0.0049	2.417		-0.440*			0.828*
ca	282	4.42	1.3	2.891	0.0572	0.14			-0.210	0.766	
cm	282	4.40	2.0	3.849	0.0224	0.437			-0.392		0.817*
am	282	4.38	2.8	5.055	0.0070	-1.473				0.856*	0.797*
kwc	281	4.29	6.9	8.02	0.0000	4.783	3.919***	-0.594**	-0.610*		
kwa	281	4.29	6.6	7.665	0.0001	0.88	3.940***	-0.418*		0.883*	
kwm	281	4.31	5.8	6.857	0.0002	1.858	3.311**	-0.506**			0.592
kca	281	4.33	5.2	6.224	0.0004	-1.424	3.776***		-0.231	0.939*	
kcm	281	4.34	4.5	5.44	0.0012	-0.352	3.144**		-0.454		0.591
kam	281	4.32	5.7	6.763	0.0002	-2.683	3.405**			1.038**	0.548
wca	281	4.39	2.6	3.533	0.0153	4.217		-0.443*	-0.396	0.42	
wcm	281	4.36	4.0	4.934	0.0024	4.403		-0.500**	-0.499		0.799*
wam	281	4.36	3.6	4.562	0.0039	1.301		-0.361		0.672	0.798*
cam	281	4.39	2.6	3.535	0.0153	-0.753			-0.198	0.728	0.792*
kwca	280	4.28	7.1	6.4	0.0001	3.179	4.018***	-0.512*	-0.447	0.551	
kwcm	280	4.28	7.3	6.591	0.0000	4.148	3.575**	-0.581**	-0.586*		0.539
kwam	280	4.29	7.0	6.309	0.0001	0.419	3.595***	-0.413*		0.838*	0.534
kcam	280	4.32	5.6	5.23	0.0004	-1.889	3.428**		-0.221	0.897*	0.54
wcam	280	4.36	3.9	3.874	0.0044	3.306		-0.441*	-0.384	0.385	0.788*
kwcam	279	4.28	7.4	5.543	0.0001	2.669	3.682***	-0.504*	-0.435	0.517	0.517

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

Table 18: Fits of regression models, corn, omitting values over 75 kg/ha initial or final Morgan's P (N=228)

Model	df	stderr	Adj R^2 %	F	pvalue	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
	227	2.39				0.066					
k	226	2.35	3.3	8.723	0.0035	-0.676	2.051**				
w	226	2.39	0.4	1.805	0.1805	1.170		-0.153			
c	226	2.39	0.2	0.538	0.4639	-0.328			0.138		
a	226	2.36	3.0	7.917	0.0053	-0.552				0.639**	
m	226	2.34	4.1	10.59	0.0013	-0.760					0.721**
kw	225	2.34	4.2	6.028	0.0028	0.726	2.227**	-0.204			
kc	225	2.35	3.2	4.705	0.0100	-1.124	2.069**		0.155		
ka	225	2.31	6.8	9.317	0.0001	-1.399	2.203**			0.691**	
km	225	2.32	5.8	7.93	0.0005	-1.193	1.594*				0.596**
wc	225	2.39	0.9	0.995	0.3713	0.844		-0.142	0.085		
wa	225	2.36	2.8	4.218	0.0159	0.097		-0.084		0.600*	
wm	225	2.34	4.2	6.023	0.0028	0.222		-0.134			0.707**
ca	225	2.34	4.3	6.11	0.0026	-1.916			0.411*	0.840***	
cm	225	2.34	3.9	5.562	0.0044	-1.151			0.137		0.721**
am	225	2.31	6.7	9.151	0.0002	-1.316				0.607**	0.694**
kwc	224	2.34	3.9	4.069	0.0077	0.404	2.226**	-0.192	0.084		
kwa	224	2.31	7.0	6.675	0.0002	-0.419	2.304***	-0.133		0.631**	
kwm	224	2.31	6.4	6.162	0.0005	0.062	1.772*	-0.178			0.562*
kca	224	2.29	8.6	8.107	0.0000	-2.944	2.303***		0.454*	0.914***	
kcm	224	2.32	5.6	5.504	0.0012	-1.626	1.612*		0.151		0.594**
kam	224	2.28	8.9	8.393	0.0000	-1.841	1.771*			0.655**	0.552*
wca	224	2.34	3.9	4.055	0.0078	-1.916		0	0.411	0.839**	
wcm	224	2.34	3.9	4.079	0.0076	-0.132		-0.121	0.091		0.708**
wam	224	2.31	6.4	6.206	0.0005	-0.782		-0.069		0.575*	0.688**
cam	224	2.29	8.0	7.542	0.0001	-2.625			0.398*	0.801**	0.684**
kwca	223	2.29	8.2	6.093	0.0001	-2.509	2.332***	-0.046	0.426*	0.880***	
kwcm	223	2.32	6.1	4.662	0.0012	-0.283	1.771*	-0.166	0.089		0.564*
kwam	223	2.28	8.9	6.536	0.0001	-1.005	1.870**	-0.112		0.606**	0.535*
kcam	223	2.26	10.5	7.658	8.464E-06	-3.308	1.882**		0.436*	0.871***	0.533*
wcam	223	2.3	7.6	5.636	0.0002	-2.772		0.015	0.407	0.813**	0.686**
kwcam	222	2.27	10.1	6.11	0.0000	-3.06	1.901**	-0.026	0.420*	0.852**	0.530*

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

Table 19: Fits of robust regression models, all crops, all phosphorus levels (N=747, adaptive weights 0-1)

Model	outliers	rrse	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	54	1.26	0.055					
rob-k	53	1.26	0.026	0.355				
rob-w	52	1.26	0.853		-0.118*			
rob-c	52	1.26	0.248			-0.073		
rob-a	51	1.25	-0.384				0.287***	
rob-m	55	1.25	-0.16					0.201***
rob-kw	52	1.26	0.934	0.538	-0.137*			
rob-kc	53	1.27	0.217	0.356		-0.072		
rob-ka	52	1.25	-0.498	0.728			0.322***	
rob-km	54	1.25	-0.186	0.326				0.200***
rob-wc	52	1.26	1.186		-0.128*	-0.099		
rob-wa	52	1.25	0.147		-0.074		0.267***	
rob-wm	54	1.25	0.599		-0.111			0.195***
rob-ca	52	1.25	-0.733			0.103	0.337***	
rob-cm	55	1.25	0.046			-0.079		0.203***
rob-am	54	1.24	-0.587				0.284***	0.194***
rob-kwc	52	1.27	1.271	0.55	-0.147*	-0.101		
rob-kwa	52	1.25	0.176	0.831	-0.096		0.301***	
rob-kwm	53	1.25	0.674	0.494	-0.128*			0.192***
rob-kca	52	1.25	-0.969	0.812		0.135	0.392***	
rob-kcm	54	1.25	0.018	0.326		-0.078		0.202***
rob-kam	53	1.24	-0.69	0.691			0.317***	0.191***
rob-wca	53	1.25	-0.216		-0.059	0.076	0.308***	
rob-wcm	53	1.25	0.944		-0.122*	-0.104		0.197***
rob-wam	51	1.24	-0.095		-0.068		0.266***	0.192***
rob-cam	54	1.24	-0.895			0.092	0.329***	0.191***
rob-kwca	52	1.25	-0.31	0.878	-0.078	0.103	0.359***	
rob-kwcm	53	1.26	1.02	0.505	-0.139*	-0.104		0.194***
rob-kwam	53	1.24	-0.065	0.785	-0.089		0.298***	0.186***
rob-kcam	53	1.24	-1.114	0.77		0.123	0.381***	0.186***
rob-wcam	52	1.24	-0.413		-0.055	0.068	0.302***	0.190***
rob-kwcam	53	1.24	-0.503	0.83	-0.073	0.094	0.351***	0.184***

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

Table 20: Fits of robust regression models, corn, all phosphorus levels (N=285, adaptive weights 0-1)

Model	outliers	rrse	intercept	corn (k)	wetness (w)	Ca X1000 (c)	Al X100 (a)	manure X10000 (m)
(base)	9	2.48	0.113					
rob-k	9	2.49	-0.65	2.150*				
rob-w	9	2.45	1.643		-0.212			
rob-c	9	2.49	-0.885			0.362		
rob-a	9	2.44	-0.355				0.470*	
rob-m	9	2.48	-0.494					0.546*
rob-kw	9	2.47	1.247	2.370*	-0.274*			
rob-kc	9	2.50	-1.675	2.154*		0.368		
rob-ka	9	2.46	-1.309	2.383*			0.577**	
rob-km	10	2.50	-1.018	1.867*				0.419
rob-wc	9	2.47	0.577		-0.18	0.302		
rob-wa	9	2.43	0.842		-0.154		0.385	
rob-wm	10	2.46	0.881		-0.184			0.502
rob-ca	10	2.43	-2.527			0.668*	0.794***	
rob-cm	9	2.49	-1.549			0.374		0.563*
rob-am	11	2.44	-0.938				0.461*	0.531*
rob-kwc	9	2.48	0.227	2.355*	-0.243	0.289		
rob-kwa	9	2.45	0.247	2.515**	-0.208		0.473*	
rob-kwm	9	2.48	0.760	2.120*	-0.247			0.341
rob-kca	10	2.44	-3.713	2.493**		0.722**	0.931***	
rob-kcm	9	2.51	-2.055	1.857*		0.37		0.427
rob-kam	9	2.46	-1.635	2.114*			0.560**	0.391
rob-wca	10	2.44	-2.279		-0.025	0.652*	0.773**	
rob-wcm	9	2.48	-0.311		-0.147	0.325		0.527
rob-wam	11	2.44	0.060		-0.126		0.396	0.505
rob-cam	11	2.43	-3.197			0.682**	0.796***	0.557*
rob-kwca	10	2.45	-2.946	2.554**	-0.082	0.674*	0.868***	
rob-kwcm	9	2.5	-0.325	2.084*	-0.213	0.3		0.359
rob-kwam	9	2.46	-0.238	2.266*	-0.182		0.475*	0.342
rob-kcam	10	2.44	-4.019	2.201*		0.717**	0.913***	0.391
rob-wcam	11	2.44	-3.343		0.014	0.692*	0.809**	0.562*
rob-kwcam	10	2.46	-3.544	2.254*	-0.05	0.688*	0.876***	0.378

*Coefficient significance codes: *** = 0.001, ** = 0.01, * = 0.05, blank = not significant at >0.05*

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