Phosphorus Index for Vermont: Background, Rationale, and Questions

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The Phosphorus Index is a tool developed to assess the potential for phosphorus runoff from individual fields based on soil and field characteristics and on management practices. Use of the P Index provides a means of identifying fields that have high P runoff potential and, therefore, require additional conservation practices and/or limitations of manure or fertilizer P application, as well as fields that have low or moderate potential for P runoff. The P Index provides a relative rating as to the risk of P runoff from individual fields, which can be used to prioritize fields for nutrient and soil management practices. It does not attempt to estimate actual quantity of P lost in runoff.

The purpose of this document is to provide background and rationale for a version of the P Index developed for Vermont. A draft of the Vermont P Index is presented in the accompanying document, *The Phosphorus Index: A Tool for Management of Agricultural Phosphorus in Vermont*.

Development of the Phosphorus Index: A Very Brief (and Incomplete) Summary

All versions of the P Index include a number of site characteristics involved in the source, transport, and management of P that relate to runoff of P from agricultural fields. The original version of the P Index (Lemunyon and Gilbert, 1994; NRCS, 1994) included the following factors, or site characteristics:

a) soil erosion
b) irrigation erosion
c) soil runoff class
d) soil test P
e) P fertilizer application rate
f) P fertilizer application method
g) organic P application rate
h) organic P application method

Each site characteristic, is assigned a P loss rating with a corresponding numerical value: None (0), Low (1), Medium (2), High (4), or Very High (8); each characteristic is given a weighting factor reflecting its relative importance in contributing to P runoff (0.5 to 1.5). The P Index is calculated by multiplying each P loss rating by its corresponding weighting factor and summing the results. The P Index for an individual site or field places it into a category (Low, Medium, High, or Very High) with associated interpretations and recommendations for soil and nutrient management.

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Later versions of the P Index have added or proposed new factors and/or incorporated changes in how P loss ratings are calculated or combined to obtain a P Index. Additional factors have included (not an exhaustive list):

a) Distance to water body (McFarland et al., 1998)
b) Vegetation/grazing management (McFarland et al., 1998)
c) Hydrologic sensitivity (slope gradient and length, flooding frequency, drainage class, presence of concentrated flow) to replace Runoff potential/class (Klausner, 1995; Klausner et al., 1997)
d) Degree of P saturation, estimated by (Melich III-P/Melich III-Al) (Bolinder et al., 1998)
e) Contributing distance, or return period (Gburek, 1998)
f) P leaching, where this is considered a significant process (Sims et al., 1998)

In most versions of the P Index, all factors are additive. This means that all factors are considered equivalent (with adjustments for variable weighting of individual factors) and there is no accounting for interaction among terms. The modification proposed by Gburek et al. (1998), in addition to adding a “contributing distance” variable, divides the various parameters into two groups – P transport (soil erosion, irrigation erosion, runoff class, and contributing distance) and P source (soil test P and rate and application method of both fertilizer and organic P source). The P transport factors receive rating values of less than one and are multiplied together to yield an overall “P transport potential” with a value between 0 and 1.0. The P Source Potential value (sum of individual source factor values, as in earlier versions) is then multiplied by the P Transport Potential value. Thus, the P Transport Potential value serves as a scaling factor that reduces the full P Source Potential by some proportion as an estimate of the potential P source that actually moves off the field in runoff. This means that a field with a very high P source potential (for example, a field with a very high soil test) but a low or moderate P transport potential would not likely receive a high PI rating because there is a low probability that P would be transported from the field.

A Modified P Index for Vermont

The Phosphorus Index for Vermont is based on the original Phosphorus Index referred to earlier (Lemunyon and Gilbert,1993; NRCS, 1994). It also incorporates a number of ideas from modified P Index versions from other states (McFarland et al., 1998; Klausner et al.,1997; Gburek et al, 1998), others from discussions at a meeting of a Northeast P Index working group (including Coale and Layton, 1999), as well as some from our own work in Vermont (Jokela et al., 1998; Magdoff et al., 1999).

The proposed P Index for Vermont uses a set of site characteristic factors that are primarily from earlier versions of the P Index (Table 1), but we have included several new ones. And we have taken a different approach in calculating the P Index, in an attempt to account for functional interactions among various site characteristics. Interpretations are similar to other versions (Table 2).

What's New? Site Characteristics

Modified Morgan's Soil Test P Extractant

The University of Vermont has used the Modified Morgan's extractant (1.25 *M* NH_4Acetate, pH 4.8) since the 1960's when it was introduced by McIntosh (1969). Either the Morgan's (NaAcetate) or the Modified Morgan's extractants, which are equivalent for phosphorus, are used in New York and most of New England (ME, MA, CT, RI, and VT), as well as by some labs in Washington and Oregon. The Modified Morgan's was the obvious choice for the P Index in Vermont because it is the extractant used in our crop nutrient recommendations (Jokela et al., 1998b). For the same reason, Morgan's soil test P was part of the P Index proposed for New York by Klausner (1997).

Modified Morgan P has shown a very strong correlation with water soluble and $CaCl_2$ solution P (Figure 1; Jokela et al, 1998a; Magdoff et al, 1999), both of which have been used as measures of soil P available for release into runoff.

Modified Morgan P also serves as an index of P saturation, as supported by the correlation of Modified Morgan P with the ratio of reserve P/reactive Al (Magdoff et al., 1999). (Reserve P = Modified Morgan extractant + F; reactive Al = Modified Morgan Al).

Reactive Aluminum

When manure or fertilizer is incorporated in the soil, the effect of the applied P on runoff P concentration is primarily a function of increased soil P enrichment as indicated by an increase in P soil test. Different soils, however, vary greatly in the P test increase that results from a given P addition. Aluminum extracted by Modified Morgan solution, termed "Reactive Aluminum" (Lee and Bartlett, 1977), is a good indicator of how much the addition of P as manure or fertilizer will increase soil test P. Those testing low to moderate in Al show a much greater increase in soil test P than those testing high. (Figure 2; Magdoff et al., 1999; Jokela et al., 1998a)

Flooding Frequency

Particulate and soluble P removed from a field during flooding events can be a significant contribution to P loading of a stream. We have added a "flooding frequency" factor, as defined for soil mapping units in the NRCS soil survey data base. This term was suggested by Klausner (1996) as one of five factors in a Hydrologic Sensitivity factor.

Vegetated Field Buffer

A vegetated buffer strip at the edge of a cropped field can retain a portion of the phosphorus in runoff, especially that in the particulate form. Preliminary results from a field study in Addison, VT, show significant reductions in runoff P and sediment concentrations from the establishment of grass-legume buffer strips at the field edge

(Jokela et al, 1999). The P Index buffer width is defined as the distance of grass or other close-seeded vegetation, woody species, or a combination from field-edge to waterway or path of seasonal concentrated flow. No manure or P fertilizer is to be applied to the buffer area.

Site Characteristics Not Included

Irrigation Erosion

The use of irrigation is so limited in Vermont that we have not included it in the P Index. If it is a factor in local situations it can be added.

Phosphorus Leaching

Our P Index assumes that the dominant loss mechanism for loading of P into surface waters is surface runoff. Limited observational data in Vermont have shown only minimal amounts of P lost via leaching. We recognize that in some other locations and soils P leaching may be significant and should be included (Sims et al., 1998).

Contributing Distance or Return Period

Gburek et al. (1998) proposed use of the concept of return period, or contributing distance, a hydrologic term representing the probability of runoff as a function of distance from a stream. This would be a valuable addition to the P Index, but we were unable to determine how to use it on a range of fields in different watersheds without monitoring data to support the relationship between distance-to-stream and runoff probability. Consequently, we have not included it in our P Index.

What's New? Method for Calculating P Index

Separation of Source and Transport Factors

We separated P Index factors into source and transport potential categories, as proposed by Gburek et al. (1998), and used the transport potential factor in a multiplicative way to adjust the source potential (Table 1). While this is not a new approach, it is different from most earlier versions.

Use of P Application Management Factors

While P Application Method/Timing is included in the P source group, we see it as modifier of the organic and fertilizer P rate factors, rather than as another term to be added to P rate and soil test P. Phosphorus management is not an independent factor, but one that interacts with P rate to determine the actual availability of the applied P for transport in runoff. More specifically, organic or fertilizer P applied on the surface in the most vulnerable time period is assumed to have full, or maximum, susceptibility for runoff, and receives a coefficient of 1; whereas P applied with improved methods or timing is assigned a value less than 1 to reflect a reduced availability for runoff (Table 1). Each P management coefficient is multiplied times P rate factors for manure and fertilizer P to create modified P rate values.

Use of Reactive Aluminum Test

We have incorporated the Reactive Al test, described above, into the P Index as a modifier for incorporated (i.e. non-surface-applied) manure or fertilizer. Depending on the reactive Al test level, a field has a coefficient ranging from 0.6 to 1.0, which is multiplied times the P Rate-Method value (Table 1). Soils testing lowest in reactive Al (<20 ppm) show the greatest increase in soil test P (Fig. 2) and receive a value of 1.0; those testing higher in Al receive lower coefficients to reflect the lower expected soil test P increase. If manure is not incorporated, the presence of manure on the surface will tend to outweigh the effect on increased soil test P, so no adjustment for Al is made.

Buffer Width

The value for the buffer width factor ranges from 0.7 to 1.0, depending on width (Table 1). This coefficient is multiplied times the preliminary P Transport Potential to reflect the portion of P in runoff that is retained in the buffer strip. (This same approach could be used to account for the effect of other BMPs that are expected to reduce P runoff.)

Combining Site Characteristic Values to Calculate Source and Transport Potentials

P Source Potential is calculated by adding values from three sources – soil test P, fertilizer P, and organic P. This is similar to the method used in most P Index systems except that the P rate variable is modified by the P method/timing factor (and reactive Al for non-surface applied P), rather than considering P method a separate additive value (Table 1).

P Transport Potential is calculated so as to give a resulting value that is between 0.1 (approximately) and 1.0. This is done by adding the values for erosion, runoff, and flooding and dividing by the sum of very high, or maximum, values (and multiplying the result by the buffer width factor). Thus, if all three site characteristics were rated very high and buffer width were less than 15 feet, the P Transport Potential would be 1.0, indicating full potential for transport of the P source. For all other situations, the Transport Potential value (<1) is an estimate of the proportion of full potential expected on this field. (If Soil Erosion were greater than 15 tons/acre it could actually by greater than 1 because the erosion rating would be greater than the "very high" value.)

$$\text{P Transport Potential} = [(E+R+F)/30] \times BW \quad \text{(Value from 0.1 to 1.0)}$$

If another P transport site characteristic were to be added (e.g. P leaching, L) then its value would be added to both the numerator and denominator:

$$\text{P Transport Potential} = [(E+R+F+L)/(30+L_{max})] \times BW$$

Assigning of Values to Runoff Potential Categories

The Lemunyon and Gilbert (1994) P Index, as well as several others, assigned discreet values to each category (Low, Medium, etc.) using a base 2 system, i.e. 0, 1, 2, 4, 8. This means that higher (greater runoff potential) categories are weighted proportionally greater than lower ones. Some versions of the PI have used a system that assigns values to some variables that are linear and/or continuous functions (Klausner, 1997; Gburek et al., 1998; Coale and Layton, 1999). We chose to assign linear values to most site characteristics. For some – soil test P, fertilizer and organic P rate, and soil erosion – we assigned continuous values by multiplying by a coefficient, e.g. 0.25 x soil test P. This also means that there is no cap, or maximum, value; an exceptionally high soil test P level (or P application rate) will contribute more to the loss potential rating than a pre-assigned “Very High” value.

Other P Index systems multiply the standard loss potential value by a weighting value assigned to each site characteristic to reflect its relative importance in contributing to P runoff. We chose to incorporate the weighting factors directly into the loss potential values to simplify the calculations since the values assigned to each category varied with site characteristic anyway. For example, for P Transport Potential the unweighted Very High value would be 10 for soil erosion, runoff class, and flooding frequency. When they are multiplied by weights of 1.5, 1.0, and 0.5 the very high values become 15, 10, and 5, respectively (Table 1).

Application of a P Index to Nutrient Management Planning

General Nutrient Management Planning

A P Index can play an important role in nutrient management planning by calling attention to those fields that require additional conservation practices or more careful nutrient management to avoid P runoff problems. It can also indicate on which fields current practices can be maintained without the likelihood of water quality problems. A logical approach would be as follows:

a) Develop a whole-farm nutrient management plan, which includes application rates and methods of manure and fertilizer P for all fields.
b) Calculate a P Index for each field based on planned management.
c) Modify management practices on fields with P Index ratings higher than acceptable and rerun P Index. This may include reducing manure application rates (or shifting to other fields), changing method/timing, etc. Repeat until all fields have acceptable P Index ratings.

Because of the time requirement to develop P Indices for all fields on a farm, especially the in-field measurements needed to estimate soil erosion with RUSLE, an alternative would be to limit P Index calculations to those fields that are suspected of having serious P runoff problems. (See later discussion.)

P Index as a Guide to Manure Application

A more specific use of the P Index is as a guide for determining acceptable application rates of manure on cropland. Recent guidelines by NRCS state that manure application rates are to be based on one of three options – P Index, P threshold, or soil test P (NRCS, 1999). If the P Index is used, the guidance provides that for Low or Medium Risk (P Index rating) manure rate can be N-based, for High Risk is to be P-based (e.g. crop removal), and for Very High Risk P-based (e.g. no application). Maryland has followed a similar approach in recent nutrient management legislation (Coale and Layton, 1999).

This use of the P Index raises an interesting question. Since one of the parameters in the P Index calculation is manure application rate, how can the P Index be used to determine what the application rate should be? One approach for dealing with this would be to first calculate a P Index with only manure that has already been applied for the season (e.g. fall-applied). Then, depending on the resulting P Index, calculate a new P Index with the proposed manure rate. If the resultant P Index rating is too high to be acceptable then reduce the manure application rate (or adjust other management factors) and recalculate the P Index.

Clarification of "Phosphorus-based"

The term "Phosphorus-based" has been used recently as related to manure application rate. (See above in reference to NRCS guidelines.) In general, it indicates a manure rate based on the phosphorus content of manure and/or P in the soil or crop. More specific language is needed to clarify the meaning of "P-based". The term can refer to application based any of the following:
a) P crop need based on P soil test
b) Crop P removal
c) P soil test threshold level, e.g. no manure to be applied if soil test P>200 ppm

While the ideal would be to base application rate on P crop need, in areas with predominately high or excessive P soil tests this would mean eliminating manure application entirely. The alternative of limiting P to crop removal amounts should at least prevent increasing soil test P levels.

Screening Tool Options: Soil Test P or Runoff Potential?

Developing a P Index requires a site visit to measure slope and other field characteristics needed for estimating soil erosion and other parameters. This may make it impractical to run a P Index on all fields where nutrient management planning is being implemented on a large scale, whether by legislation, cost-share requirements, or other reasons. Consequently, it is desirable to have a screening tool to prioritize those fields most likely to have P runoff problems and, therefore, having the greatest need for a P Index.

Legislation in Maryland, referred to above, uses soil test P level (expressed in the form of a Fertility Index Value) as a screening tool, requiring a P Index as a guide to manure application if the P soil test is above a given threshold level (Coale and Layton, 1999). Several other states (CO, KS, ME, MS, OK, TX) have policies or legislation that use a P soil test to restrict manure application (Lory and Scharf, 1999). Use of a P soil test has the advantage of being an easily quantifiable measure that is already in common usage. And fields with higher P soil tests tend to have runoff with higher *concentrations* of soluble P (though not necessarily higher *quantities* of P).

However, the main consideration should be to avoid applying manure on fields where application would result in the greatest *increase* in P runoff. This is primarily a function of runoff and erosion potential (or the P Transport part of the P Index) and is not dependent on soil test P. Manure application increases the P source available for transport in runoff, so the greatest impact of the manure P addition will be on fields that have the highest potential to transport that P in runoff. Consequently, where a full P Index can not be run on all fields, we are proposing use of a quick P runoff estimate by means of a Phosphorus Runoff Screening Matrix (PRSM) (Table 3). It includes parameters that can be determined directly from soil survey database (runoff class, HEL classification, and flooding frequency) along with soil test P and, consequently, does not require on-site field measurements. If any of the parameters in the PRSM fall in the High category then the full P Index must be determined to obtain a more complete estimate of P runoff potential.

Another consideration in comparing fields could be the effect of manure application on increasing other components of the P Source, namely P soil test level. Is current soil test level a good indicator of the degree to which soil test P will be increased by manure application? Data from Vermont shows a poor relationship between Modified Morgan's soil test P and the increase in soil test P with P addition (Figure 3). (Reactive aluminum might be a more useful parameter for this purpose. (Figure 2)) Soil test P was included in the PRSM primarily to avoid the use of fields with low or medium runoff potential as disposal sites. Even fields that are not considered high in runoff potential will sometimes have significant runoff events, which can be quite serious if soil is highly enriched in P.

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Table 1. The Phosphorus Index for Vermont: site characteristics and P runoff potential ratings.

Site characteristic	**Phosphorus Source Potential Rating**			
	Low/None	Medium	High	Very High
Soil Test P, ppm, Mod. Morgan's	(0-8 ppm)	(8.1-20)	(20.1-40)	(>40)
	0.25 x Soil Test P			
Fertilizer P Rate lb P_2O_5/acre	**0.2 x lb P_2O_5/acre**			
Fertilizer P Application Method/Timing	Inject/sub-surface band **0.4**	Broadcast and incorporate **0.6**	Surface-applied May-Sept. **0.8**	Surface-applied Oct.-April **1.0**
Organic P Rate lb P_2O_5/acre	**0.2 x lb P_2O_5/acre**			
Organic P Application Method/Timing	Inject or sub-surface band **0.4**	Broadcast and incorporate **0.6**	Surface-applied May-Oct **0.8**	Surface-applied Nov-April **1.0**
Reactive Aluminum, Mod. Morgan's, ppm	>80 ppm	41-80	21-40	<20
	0.6	**0.7**	**0.8**	**1.0**

P Source Potential = STP + (FP Rate x FP Meth x Al) + (OP Rate x OP Meth x Al)
Note: Use Al factor only for non-surface-applied fertilizer or manure.

Site characteristic	**Phosphorus Transport Potential Rating**			
	Low/None	Medium	High	Very High
Soil Erosion (E) tons/acre/yr	(0-5)	(5-10)	(10-15)	(>15)
	1.0 x tons soil loss/acre/yr			
Soil Runoff Class (R)	Low/ V. Low **4**	Medium **6**	High **8**	Very High **10**
Flooding Frequency (F)	Rare/None **0**	Occasional **3**	---	Frequent **5**
Buffer Width (BW), ft.	>100 **0.7**	41-100 **0.8**	16-40 **0.9**	<15 **1.0**

P Transport Potential = [(E+R+F)/30] x BW (Value from 0.1 to 1.0)

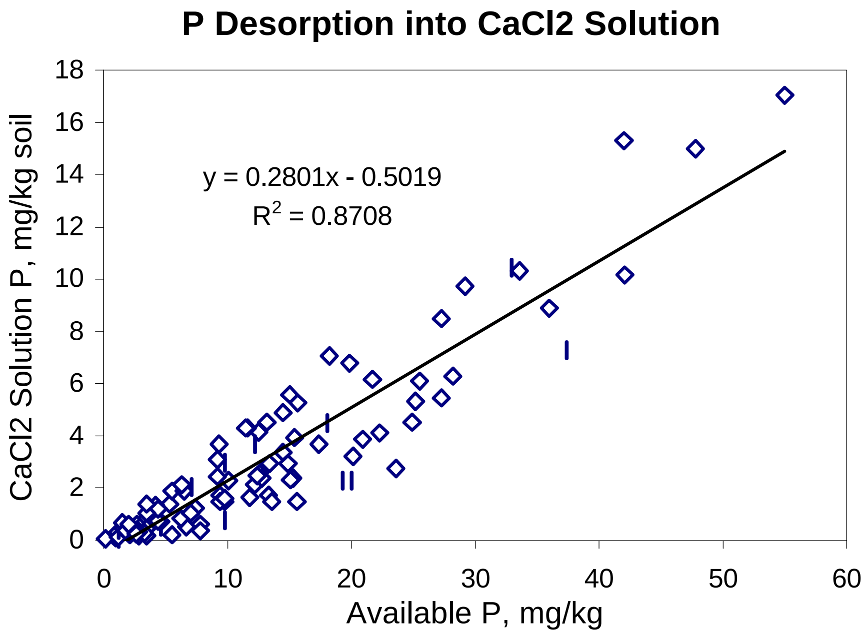
P Index = P Transport Potential x P Source Potential

Table 2. Interpretation for the Phosphorus Index. (NRCS, 1994)

Phosphorus Index	Site Interpretations
<6	**LOW** potential for P movement from site.
6-12	**MEDIUM** potential for P movement from site. Chance for an adverse impact to surface water exists.
12.1-25	**HIGH** potential for P movement from site and for an adverse impact on surface waters to occur unless remedial action is taken.
>25	**VERY HIGH** potential for P movement from site and for an adverse impact on surface waters. Remedial action is required to reduce the risk of P movement.

Table 3. `Phosphorus Runoff Screening Matrix (PRSM)

	Low	Medium	High
Runoff Class	Very Low or Low	Medium	High
HEL Class (Highly Erodible Land)	Non-HEL	Potentially HEL	HEL
Flooding Frequency	None/Rare	Occasional	Frequent
Soil Test P, ppm (Mod. Morg.)	7 or less	7.1-20	>20
P Runoff category is determined by the highest category of any individual parameter.			



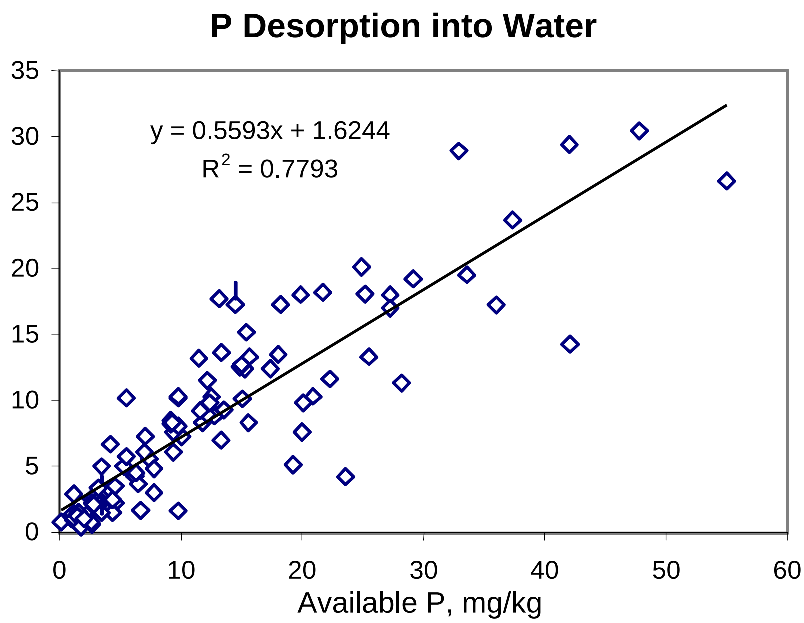


Figure 1. P extracted by 0.01 M $CaCl_2$ solution (top) or water (bottom) as a function of Modified Morgan P in 54 soils. (Jokela et al., 1998; Magdoff et al., 1999).

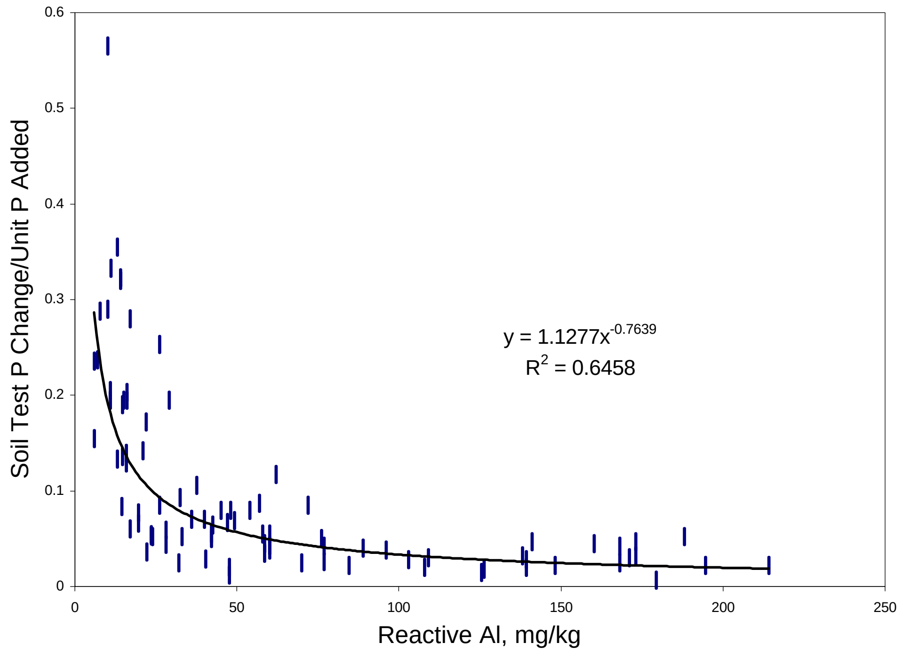


Fig. 2. Change in soil test P (Mod. Morgans) with P addition as a function of reactive Al. (Jokela et al., 1998; Magdoff et al., 1999)

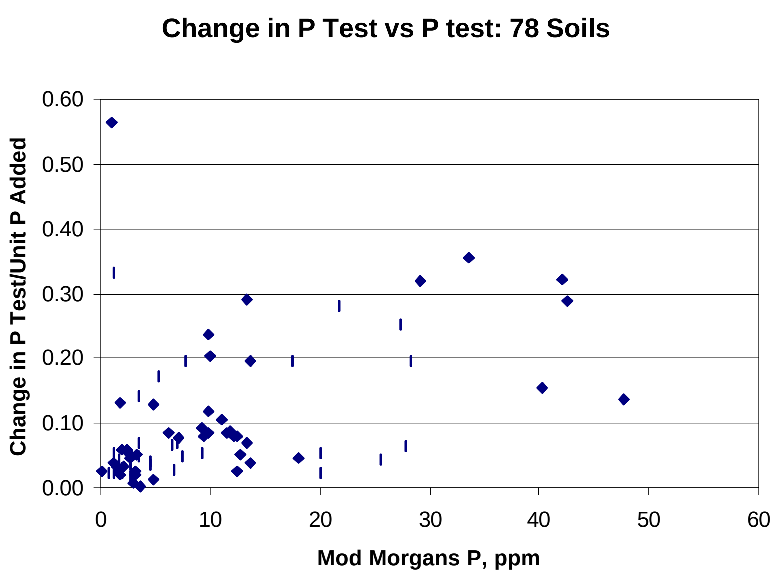


Fig. 3. Change in soil test P (Mod. Morgans) with P addition as a function of soil test P.