EVALUATION OF SOIL P AND K EXTRACTANTS FOR SOILS AND CROPS OF HAWAII

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ABSTRACT

Four greenhouse pot experiments were conducted to evaluate the performance of P and K extractants on two Hawaiian soils in terms of their correlations with the performance of two crops that are grown in Hawaii. The extractants assessed were Modified Truog, Mehlich3, Olsen, and Resin for P and NH_4OAc, Mehlich3, and Resin for K. The Modified Truog, Olsen, and NH_4OAc extractants are commonly used in Hawaii. The Mehlich3 and Resin extractants have not been well tested here yet, but their capacity to extract both P and K simultaneously is a potential advantage over the other methods. The soils were an Ultisol and an Andisol, both of which were amended to establish a wide range of soil P and K concentrations.

For both soils, Mehlich3 P and Resin P were as well related with plant response parameters (dry matter yield and P uptake) as were Modified Truog P and Olsen P. Test values from all four methods were very well correlated with one another, with Resin P being slightly less well correlated than other three. In term of the accuracy of diagnoses, the sensitivity of P test values to change of soil P levels, and C.V. for sampling, Mehlich3 usually ranked between Olsen and Modified Troug extraction methods while Resin P performed worst overall.

Mehlich3 K perfomed as well as NH_4OAc K in both soils for crop tested in terms of the coefficients of determination for

regressions of K uptake and K applied with K extracted, and in terms of the sensitivity of K test values to the change of soil K levels and the C.V. for sampling. In both soils, however, Resin K was as well correlated with NH_4OAc K as was Mehlich3 K. However, in terms of the sensitivity of K test values and the C.V. for sampling, Resin K usually did not perform as well as the other methods.

These results suggest that it would be practical to switch from the conventional procedures, with separate extractions for P and K, to a simultaneous P and K extraction with Mehlich3 for these soil-crop combinations. Use of a simple linear regression model would allow conversion between results obtained from a Mehlich3 P and K extraction and those obtained from Modified Truog P, Olsen P, and NH_4OAc K extractions.

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CHAPTER 1

INTRODUCTION

Due to limited energy supplies, rapid population growth, and the need for environmental protection, prediction of optimal fertilizer rates has become both more challenging and more critical to the viability of agricultural systems. More precise estimates of crop requirements and responses are needed to make decisions that are both economically and ecologically sound. Soil testing and plant analysis for the guidance of management and fertilizer recommendations are playing an increasingly important role in meeting this need.

The purpose of soil testing is to provide soil information that is necessary for making sound fertilizer recommendations. It can be considered a method for transferring research information to soils for which field experimental data are not available (Evans, 1987). Because it is not practical to conduct a fertility trial on every field for each crop that might be grown, the most satisfactory way to transfer soil testing technology is by arranging crops and soils into manageable groups. Soil test calibration on representative members of these groups is then basic to a good soil testing program. Without a background of information on the relationships between crop response and soil test levels of plant nutrients, the values for extracted nutrients have little meaning (Evans, 1987). Although the importance of soil test calibration as a tool to enhance the

value of soil tests is now widely recognized (Tisdale, 1985), very little research on soil test calibration was conducted prior to the 1950s, and little faith in its use existed among most professional agronomists except in the diagnosis of acid and alkali conditions (Olsen et al., 1987).

Much calibration work has been done by soil testing laboratories on the U.S. mainland, but results from these studies do not apply to tropical soils such as Oxisols, Ultisols, and Andisols, or to many of the crops that are important in tropical areas (Silva, 1991). Thus it is necessary to conduct the calibration with relevant soils and crops. Although some calibration work has also been done in Hawaii, more is needed to verify and update soil test calibration information. Changing management practices also contribute to the need for continually conducting soil test calibration studies (Olsen et al., 1987; Tisdale et al., 1985).

Although several extracting solutions have been developed for soil testing, especially for soil P and cations, extractants generally have limitations for some soil types. Most soil testing laboratories prefer a relatively fast chemical method to determine soil nutrients to use in formulating the fertilizer recommendations for crops cultivated on a wide range of soils. The search for more convenient testing methods and more widely applicable extractants remains a practical necessity.

The physical and chemical properties of soils in Hawaii vary widely because they have developed from different parent materials and under different conditions. In soils developed from acid materials, the available P is mainly in the form of Al-P and Fe-P. In moderately calcareous soils formed from marine silt or clay, Ca-P predominates. Currently, the Agricultural Diagnostic Service Center (ADSC) of the University of Hawaii is using two soil P extractants, Modified Truog for soils with pH less than 7 and Olsen for soils with pH greater than or equal to 7. ADSC currently uses 1 *M* NH_4OAc (pH = 7) for extraction of soil cations. Using different extraction methods for different soil types and different ions due to the limitations of the extractants involves tedious preparation of several working solutions and introduces additional work with each extracting procedure that is required. Also, the results obtained from different methods are difficult to compare or transfer. It would thus be helpful to find an extractant that works for more than one ion and on a wide range of soils in Hawaii.

OBJECTIVES

1. To evaluate extraction methods for soil P and K in relation to the growth of selected crops on an Andisol and an Ultisol.

2. To conduct a preliminary calibration of soil P and K tests for selected crops and soils under greenhouse conditions.

CHAPTER 2

PREVIOUS STUDIES

Phosphorus

The role of phosphorus as one of the most important elements required for crop growth has attracted much attention for many decades. Plants take up P from the soil solution which makes up only a very small portion of total soil P (Tiessen, 1993). In most soils insoluble Fe-P, Ca-P, and Al-P account for the main portion of soil P. Solution P is constantly replenished by hydrolysis of labile P or by mineralization of organic P. Soil tests for plant available P, therefore, should include solution P and the fraction of solid P which is potentially available to plants (Tiessen, 1993). Many factors affect the rate and magnitude of transformations between potentially available P and solution P. The development of an extractant that takes all major factors into account so that it could be used for all soils, the so-called "universal extractant", has been shown to be extremely difficult and no such extractant yet has been developed. For this reason and others, a number of different soil P extraction methods have been developed for different soils and conditions (Table 1).

These extractants can be grouped into several categories (Kamprath and Watson, 1980):

1) Dilute concentrations of strong acid solutions, such as Truog, Mehlich-1, etc.

Table 1. Summary of common P extraction methods.

Common name	Extractant	Soil/ solution ratio	Reference	Year developed
Bray-1	0.025N HCl + 0.03N NH_4F	1:10	Kamprath & Watson (1980)	1945
Bray-2	0.1N HCl + 0.03N NH_4F	1:17	"	
Truog	0.002N H_2SO_4 buffered at pH 3 with $(NH_4)_2SO_4$	1:100	"	1930
Modified Truog	0.02N H_2SO_4 + 0.3% $(NH_4)_2SO_4$	1:100	Ayres & Hagihara (1952)	1947
Citric acid	1% citric acid	1:10	"	1849
Egner	0.02N Ca lactate + 0.02N HCl	1:20	"	1960
Morgan	0.54N HOAc + 0.7N NaOAc pH4.8	1:10	"	1941
Olsen	0.5N $NaHCO_3$ pH 8	1:20	"	1954
Warren & Cooke	0.3N HCl	1:2	Mamo & Haque (1990)	1965
Dabin	2.5% NH_4F in 0.5N $NaHCO_3$ pH8.5	1:50	"	1967
Williams & Stewart	2.5% acetic acid	1:40	"	1941
AB-DTPA	1M NH_4HCO_3 + 0.005M $NaHCO_3$	1:2	Labhsetwar & Soltanpour(1985)	1977
Na_2-EDTA	0.02M Na_2-EDTA	1:25	"	1962

Table 1 Continued

Mehlich1	0.05N HCl + 0.025N H_2SO_4		Mehlich (1984)	1954
Mehlich2	0.2M NH_4Cl +0.2M HOAc + 0.015M NH_4F + 0.012M HCl		Nesse et al. (1988)	1978
Mehlich3	0.2N HOAc + 0.25N NH_4NO_3 + 0.015N NH_4F + 0.013N HNO_3 + 0.001M EDTA	1:12	Mehlich (1984)	1984
P sorption	0.01M $CaCl_2$ with 6 days incubation	1:10	Fox & Kamprath (1977)	1977
$CaCl_2$	0.01M $CaCl_2$	1:2	Azzaoui et al. (1989)	
Water	H_2O	1:2	Olsen & Sommers (1992)	
Isotopic Dilution of ^{32}P	^{32}P solution diluted with $5*10^{-6}$M KH_2PO_4		"	
Resin	ion or anion exchange resin		Skogley et al. (1990)	

2) Dilute concentrations of strong acids plus complexing ion(s), such as Bray-1, Bray-2, Mehlich-3, etc.

3) Dilute concentrations of salts or weak acids, such as $CaCl_2$, citric acid, etc.

4) Buffered alkaline solutions, such as Olsen extractant.

5) Extractants using exchange mechanisms such as isotopic dilution of ^{32}P and resin.

The mechanisms involved in P extraction can also be grouped as follows:

1. Solvent action of acids. Solutions with low pH can increase the solubility of Ca-P, Al-P and Fe-P.

2. Anion replacement. Anions such as acetate, sulfate, and bicarbonate can replace phosphate adsorbed on the surface of $CaCO_3$, $Al(OH)_3$, and $Fe(OH)_3$.

3. Complexing of binding cations. Fluoride, DTPA, and EDTA can complex Al and thus release P.

4. Hydrolysis of cations binding P. The OH^- ions in extractants can hydrolyze Al and Fe compounds and thus extract P (Kamprath and Watson, 1980).

5. Approximation of the natural soil solution or simulation of plant P uptake mechanisms.

EVALUATION OF COMMONLY USED P EXTRACTION METHODS

Much research to evaluate the many extracting methods for soil P has been done in many countries. One of the most complete comparative studies was conducted in Canada (Tran et

al., 1990). In that study Mehlich-III was compared with Bray-I, Mehlich-I, Mehlich-II, Olsen, HCO_3^- exchange resin and F^- exchange resin. The results indicated that Mehlich-III-P was generally well correlated with other chemical methods. On very acid soils containing large amounts of amorphous Al, Mehlich-III extracted less fixed P and was more accurate in estimating available P than the Bray-II, Bray-I, and F^--resin techniques. On acid soils containing apatite or on moderately calcareous soils, Mehlich-III was better than Bray-II, Mehlich-I, and Bray-I because this method did not strongly attack the apatite as did Bray-II and Mehlich-I. Also, Mehlich-III was less readily neutralized by free carbonates in soil than Bray-I or Mehlich-I. The Mehlich-III method also was closely related to the Olsen method and to the F^-- and HCO_3^--resin methods. Mehlich-III offered an advantage for determining soil P in the varied soils of Quebec, Canada. This study also suggested that Mehlich-III has the advantage of permitting the simultaneous determination of available K, Ca, Mg, Na, Al and micronutrients.

Matar et al. (1988) evaluated four methods, anion exchange resin, Olsen, ammonium oxalate (0.2M ammonium oxalate adjusted to pH 6.9, soil/solution ratio = 1:25, and 2 hours shaking time), and modified Egner (0.01M calcium lactate + 0.02M HCl adjusted to pH 3.8, soil/solution ratio = 1:2, and 4 hours shaking time) in a greenhouse experiment

using ryegrass. It was observed that total P uptake of ryegrass (after 72 days) was significantly correlated with P determined by both anion exchange resin (R^2 = 0.85) and Olsen (R^2 = 0.82) methods and less well correlated with the oxalate (R^2 = 0.63) and lactate (R^2 = 0.32) methods. The R^2 values for the relationship between dry matter (after 72 days) and soil P content were 0.88, 0.83, 0.41, and 0.22 for anion exchange resin, Olsen, oxalate and lactate tests, respectively. They recommended the Olsen method to estimate soil P in calcareous soils since it is simple, rapid and reproducible.

Jones and Piha (1989) recommended the Mehlich-III soil P test for Zimbabwe soils after comparing P extraction by Mehlich-I and Mehlich-III with the Cl^--resin method. They found that P extracted by Mehlich-I was half the amount of P extracted by the resin method while Mehlich-III extracted about one and one half times as much P as the resin method. Soil P extracted by Mehlich-III was highly correlated (r = 0.846) with that extracted by the resin method in soils having pH values greater than or equal to 5.9 and somewhat less well correlated (r = 0.502) in soils with pH less than 5.9, giving an overall correlation coefficient of 0.615. Soil P measured by Mehlich-I gave a very poor correlation (r = 0.298) with P extracted by the resin method.

In a similar study conducted by Nesse et al. (1988) on alkaline soils in Western Minnesota, the Bray-I, Mehlich-III,

and Olsen methods were compared with a resin method (HCO_3^--form). The results showed that in soils having 7 to 62% calcium carbonate, P determined by the Olsen method was better correlated with that of the resin method ($r = 0.943$), than was either the Mehlich-III method ($r = 0.889$) or the Bray-I method ($r = 0.617$). However, in soils with less than 7% $CaCO_3$, P values obtained by the resin method had correlation coefficients above 0.9 with P values from all the other soil tests used. Another comparative study was performed by Wolf and Baker (1985) using the Olsen, Bray-I, Mehlich-I, and Mehlich-III soil tests. The study showed that the Bray-I and Mehlich-III tests were highly correlated ($r^2 = 0.97$) and that similar quantities of P were extracted with these two methods. Bray-I, Olsen, and Mehlich-I were not as highly correlated ($r^2 \leq 0.72$), and these relationships were influenced by the texture of the soil.

In general, Bray-1, Mehlich-1, and Olsen, which were developed about 40 years ago, appear to be used most often as classical methods in comparison studies, while Mehlich-3, which is one of the most recently developed methods, is the most frequently used alternative. In most comparison studies, Bray-1, Mehlich-1, Olsen, and Mehlich-3 test values have been generally well correlated with crop response and have also been well correlated with each other in acid to neutral noncalcareous soils. The amount of soil P extracted from these soils varied, usually in the following order:

Bray-1 > Mehlich-3 > Mehlich-1 > Olsen (Tran et al., 1990; Evans and McGuire, 1990; Gascho et al., 1990; Wolf and Baker, 1985; Mehlich, 1984; Locke and Hanson, 1991; Beegle and Oravec, 1990). Often Olsen and Mehlich-3 performed better than Bray-1 and Mehlich-1.

In a very acid Spodosol, the high concentration of NH_4F in the Bray extractant released fixed Al-P, which may thus overestimate the available P. In other acid soils that contain calcareous compounds, Bray and Mehlich-1 can dissolve large amounts of Ca-P and greatly overestimate available P values (Evans and McGuire, 1990; Tran et al., 1990; Mamo and Hapue, 1991). Poor performance for Bray-1 and Mehlich-1 on calcareous soils has also been reported by Nesse et al. (1988). However, the results from Rodriguez et al. (1989) showed that there was significant correlation ($r = 0.91$) between Olsen and Bray-1 tests over a wide range of soils with soil pH values from 5.3 to 8.1.

Mehlich-3 did not perform as well as Olsen in soils containing high levels of calcium carbonate, but in general these extractants were very highly correlated over a wide range of soils, which included alkaline soils (Buondonno et al., 1992; Nesse et al., 1988). The results from comparing these two methods on 120 soils with soil pH ranging from 3.78 to 8.6 suggested that Olsen-P values could be converted to Mehlich-3-P values with simple linear equations (Buondonno et al., 1992). Although the Olsen test showed good results in

the widest range of soils among the extractants tested, it was less sensitive than Bray-1 to changes in extractable P content with plant uptake (Yerokun and Christenson, 1990). Buondonno et al. (1992) also indicated that Mehlich-3 was a more efficient P extractant than Olsen because much larger amounts of P were extracted by Mehlich-3 than by Olsen. Another potential advantage of Mehlich-3 over Olsen is that it can simultaneously extract cations and micronutrients as well as soil P.

RESIN EXTRACTION METHOD

Many researchers are interested in resin extraction methods (using either anion-exchange or ion-exchange resins), which have been used to measure the availability of plant nutrients in research applications for almost four decades (Qian et al. 1992). These extraction methods attempt to simulate nutrient absorption by plants, thus providing a more theoretically accurate basis for soil testing (Skogley et al., 1990). Raij et al. (1986) showed that resin-extractable P had higher correlation with crop response than did P extracted with 0.025M H_2SO_4. Resin test values were highly correlated with Bray-1 and Bray-2 test values in acid to neutral soils, highly correlated with AB-DTPA values in alkaline soils, and highly correlated with Mehlich-3 and Olsen values in both alkaline and acid soils (Nesse et al., 1988; Tran et al., 1990; Yerokun and Christenson, 1990). Ion exchange resin can be used to extract not only P but cations,

nitrogen, and other nutrients as well (Skogley et al., 1990; Yang et al. 1990). According to Quemener (1979), the resin technique might be particularly suitable in the tropics because feldspars, which comprise the ultimate K reserve in soils, can supply K in tropical conditions at rates affecting plant availability. The resin extraction procedure can potentially reflect this K supply. However, the extraction procedures followed in the various resin methods are not the same. Some involve using loose resin beads for extraction, while others use a resin extractor in which resin beads are contained in mesh bags (Qian et al. 1992). Some separate the resin from the soil after extraction and elute the isolated resin with a stripping solution, while others elute the soil-resin mixture directly (Quemener 1979). Many methods employ different chemicals as stripping solutions and use different extraction periods as well (Yang et al. 1990; Raij et al. 1986; Qian et al. 1992)

Nonetheless, some researchers found that extraction methods for P fertility assessment have often been unsuccessful, and fertilizer responses have been irregular in acid tropical soils that show rapid P transformations and substantial P sorption (Tiessen, 1993).

RESEARCH ON P DETERMINATION IN HAWAII

Previous research to develop reliable methods for soil and plant analysis in Hawaii has included several studies on some aspect of soil P extraction methodology. In 1952, the

Modified Truog extractant was developed for highly weathered soils in Hawaii and has been used for determining P in Hawaiian soils since then. This method showed good correlation with the Truog method (Ayres and Hagihara, 1952). The University of Hawaii's Agronomy and Soil Science Department project 134 (1963-1968) was concerned with analytical methods for determining soil P, Si, and S. Correlations between soil, tissue, and crop (grass and legume) response to Si, P, and S were reported (Silva, 1991). In 1971, the P adsorption isotherm was developed for assessment of both quantity and intensity of soil P (Fox and Kamprath, 1971). The project titled "The Nutrient Requirements of Tropical Crops" was conducted from 1975 to 1980. The response of protea flower production and tissue nutrient levels to N, P, and K applications was reported (Silva, 1991).

Potassium

Although potassium also plays an important role in crop production, much less research on K extraction methods has been reported in the literature than has been reported on P extraction. The ability of NH_4^+ to replace other cations in soils was discovered and studied as early as the 1850's (Thomas, 1977). The ammonium acetate solution, which was first used for assessing exchangeable bases in soils by Prianishnikov in 1913 (Schollenberger and Simon, 1945), has been used as a standard extraction solution almost all over

the world (Table 2). However, the soil:solution ratios used vary from 1:2.5 to 1:20 and shaking or leaching time vary from 5 minutes to 6 hours (Houba et al. 1992). Many other solutions (i.e. $NaNO_3$, NH_4NO_3, $CaCl_2$, $NaHCO_3$, Bray solution, buffered or unbuffered NH_4-oxalate, Ca- or NH_4-lactate, double acid (HCl-H_2SO_4), Morgan's extractant (NaOAc-HOAc), Truog (H_2SO_4, 0.1 M HCl+0.2 M oxalic acid), ammonium bicarbonate-DTPA, Na-tetraphenylborate in different concentrations, hot HNO_3, etc.) have been developed to assess the availability of K in soils (Novozamsky and Houba, 1987). However, many of these methods generally give exchangeable K values that are similar to those from 1 *M* NH_4OAc. Some of these methods are limited in their use to those conditions where they seem to give the best results. For example, double acid (Mehlich-1) is considered best for sandy, acid, low CEC soils, while ammonium bicarbonate-DTPA is considered best for alkaline soils (McLean and Watson, 1985).

Neutral 1 *M* ammonium acetate solution is considered as the most suitable extractant for a wide range of soil conditions (Novozamsky and Houba, 1987; McLean and Watson, 1985; Peech, 1948). However, the results by Cassman et al. (1990) showed that the quantity parameter based on 1 *M* NH_4-extractable K or on 2.5 M H_2SO_4 were significantly less precise in predicting cotton yield in potassium-fixing soils. They reported that solution-phase K concentration in soil/solution suspensions measured by 0.01 M $CaCl_2$ or H_2O were

Table 2. Methods for the Determination of Available Potassium in Different Countries.

Country	Solution	Extraction procedure Ratio	Time	other elements
Australia	1 *M* Ammonium acetate		30 min.	Na, Mg
Austria A	1 *M* Ammonium acetate		90 min.	Na, Mg, Mn
Austria B	Calcium acetate lactate (CAL)	1:20	120 min.	
Austria C	EUF		0-30, 30-35 min.	NO_3,NH_4,Al,Na,K,Mg,Ca,P
Brasil A	0.05 *N* HCl + 0.025 N H_2SO_4 (Mehlich)	1:10	5 min.	P
Brasil B	Resin extraction	2.5 cm^3 soil + 25 ml H_2O + 2.5 cm^3 cation + anion resin	16 hours	P, Ca, Mg
Brasil C	0.5 *M* H_2SO_4		15 min.	
Burkina Faso	HCl + oxalic acid		60 min.	Na
China (Taiwan)	1 *M* Ammonium acetate		30 min.	Mg
Finland	0.5 M CH_3COOH + 0.05 *M* CH_3COONH_4 (pH = 4.65)	1:10 (V/V)	60 min.	Mg
Germany A (FRG)	Double lactate or Calcium ammonium lactate			
Germany B (FRG)	EUF		0-30, 30-35 min.	NO_3,NH_4,Al,Na,K,Mg,Ca,P
Great Britain A	1 *M* NH_4NO_3	1:10	30 min.	Mg
Great Britain B	1 *M* Ammonium acetate		150 min.	
Great Britain C	1 *M* Ammonium acetate	1:10	30 min.	Mg
Honduras	1 *M* Ammonium acetate pH 4.8-7.0		10 min. pH = 4.8 30 min pH = 7	Na, Ca, Mg
Hungary	Ammonium lactate/acetic acid (pH = 3.75)	1:20	120 min.	
Ireland	Sodium acetate/acetic acid (Morgan's solution)		30 min.	P, Mg
India	1 *M* Ammonium acetate		5 min.	
Indonesia	1 *M* Ammonium acetate	1:20	30 min. (perc.)	
Jamaica	1 *M* Ammonium acetate		30 min.	Na, Mg
Jordan	1 *M* Ammonium acetate	1:5	30 min.	
Kenya	1 *N* HCl + 0.025 *N* H_2SO_4	1:5	1 hour 10 min.	Na, Mg, Mn

Table 2. Methods for the Determination of Available Potassium in Different Countries (continued).

Country	Solution	Extraction procedure Ratio	Time	other elements
Malaysia A	1 *M* Ammonium acetate		5-6 hours (perc.)	Mg, Na, Mn
Malaysia B	1 *M* Ammonium acetate		120 min.	Na, Mg
Mauritius	1 *M* HNO_3	1:10	10 min. boiling	
Mexico	1 *M* Ammonium acetate	1:5	30 min.	
Netherlands	0.1 *M* HCl + 0.2 *M* oxalic acid	1:10	120 min.	Na
New Zealand A	1 *M* Ammonium acetate		2 min.	Na, Mg
New Zealand	1 *M* Ammonium acetate		30 min.	Na, Mg, Mn
New Zealand C	1 *M* Ammonium acetate		1 drop/10 sec.	Na, Mg
Pakistan A	1 *M* Ammonium acetate		30 min.	Na
Pakistan	1 *M* Ammonium acetate		60 min.	Na
Papua New Guinea A	1 *M* Ammonium acetate	1:10	about 30 min. leaching	Na, Mg, Mn
Papua New Guinea B	1 *M* Ammonium acetate		leaching over-night	
Peru	1 *M* Ammonium acetate	1:2.5	30 min.	Na
Philippines A	1 *M* Ammonium acetate		leaching	Na, Mg
Philippines B	1 *M* Ammonium acetate		5 min.	Na, Mg
Portugal	Ammonium lactate/acetic acid (pH = 3.75)	1:20	120 min.	
South Africa A	1 *M* Ammonium acetate	1:10	30 min.	Na, Mg, Ca
South Africa B	0.5 *M* Ammonium acetate		30 min.	
Spain	1 *M* Ammonium acetate		60 min.	Na, Mg
Surinam	3% acetic acid (pH = 2.6)		30 min. night over	Na, Mg
Sri Lanka	1 *M* Ammonium acetate		30 min.	Na, Mg
Swaziland	1 *M* Ammonium acetate	1:10	20 min.	Mg
Sweden	Ammonium lactate/acetic acid (pH = 3.75)	1:20	90 min.	Mg
Virgin Islands	0.25 *N* $NaHCO_3$ + 0.01 *M* EDTA + 0.01 *M* NH_4F	1:10	10 min.	P, Mn

(Novozamsky and Houba, 1987)

the best predictors of yield across soils. Cation exchange resin, which was first used for extraction of available K in 1951, is another method considered suitable for a wide range of soils (Qian, et al., 1992; Somasiri and Edwards, 1992). However, this method has never been widely used, especially in routine soil testing, because it is more difficult and is slower in extraction than ammonium acetate.

In recent years, soil P and K extraction methods have been directed to 'universal' extractants which can extract several elements at once. Mehlich-3, AB-DTPA (ammonium bicarbonate-DTPA), ion exchange resin, etc. have been developed for this purpose.

CHAPTER 3

MATERIALS AND METHODS

Soil and Plant Materials

Two highly weathered Hawaii soils, an Ultisol (Leilehua Series---a clayey, oxidic, isothermic Ustic Kandihumult) and an Andisol (Maile Series---a hydrous, isomesic Acrudoxic Hydrudand), were used. The major properties of these two soils are given in Table 3. The P-sorption isotherm (Fox and Kamprath, 1977) characteristics were shown in Fig. 1. The mineralogical constitutions are shown in Figs. 2 and 3. The Ultisol (Leilehua) was collected from the Waiawa Correctional Facility in central Oahu at an elevation of 256 m, with an annual minimum temperature of 20 °C, an annual maximum temperature of 23 °C, and a mean annual rainfall of 1500 mm (Waiawa project, 1993). The soil collection site was in an uncultivated area just beside the Koa tree experiment of the Agronomy and Soil Science department. The vegetation on this site was California Grass (*Brachiaria mutica*) and Molasses Grass (*Melinis minutiflora*). The Andisol (Maile) was collected from the Mealani Experiment Station on the island of Hawaii at an elevation of 854 m, with an annual minimum temperature of 13°C, an annual maximum temperature of 21°C, and an annual rainfall of 1400 mm (Ikawa et al., 1985). The field had been used for a pasture fertilizer experiment for many years and the soil was collected from the control plot of this experiment, which had received no fertilizer

Table 3. Major Properties of two Soils Used in Pot Studies.†

	Ultisol (Leilehua)	Andisol (Maile)
pH:	4.8	5.0
Bulk density	1.2 g/cm^3	0.5 g/cm^3
Clay content:	83%	-
Organic C:	2.7%	24.0%
ECEC:	3.9 cmol$_c$/kg	28.2 cmol$_c$/kg
Al saturation:	62%	19.7%
Soil solution P:	0.0132 mg/L	0.01 mg/L
Mod. Truog P:	6.7 mg/kg	14.8 mg/kg
Olsen P:	3.7 mg/kg	4.02 mg/kg
NH_4OAc K:	0.21 cmol$_c$/kg	0.13 cmol$_c$/kg

† Clay content, organic C, ECEC, and Al saturation for the Ultisol and bulk density and Al saturation for the Andisol cited from Soil Survey Investigations Report No. 29 (1976). Bulk density of the Ultisol was estimated based on bulk density of the Paaloa soil from Soil Survey Investigations Report No. 29 (1976). Organic C, ECEC, and Mod. Truog P for the Andisol were provided by Jim Jackman (unpublished data).

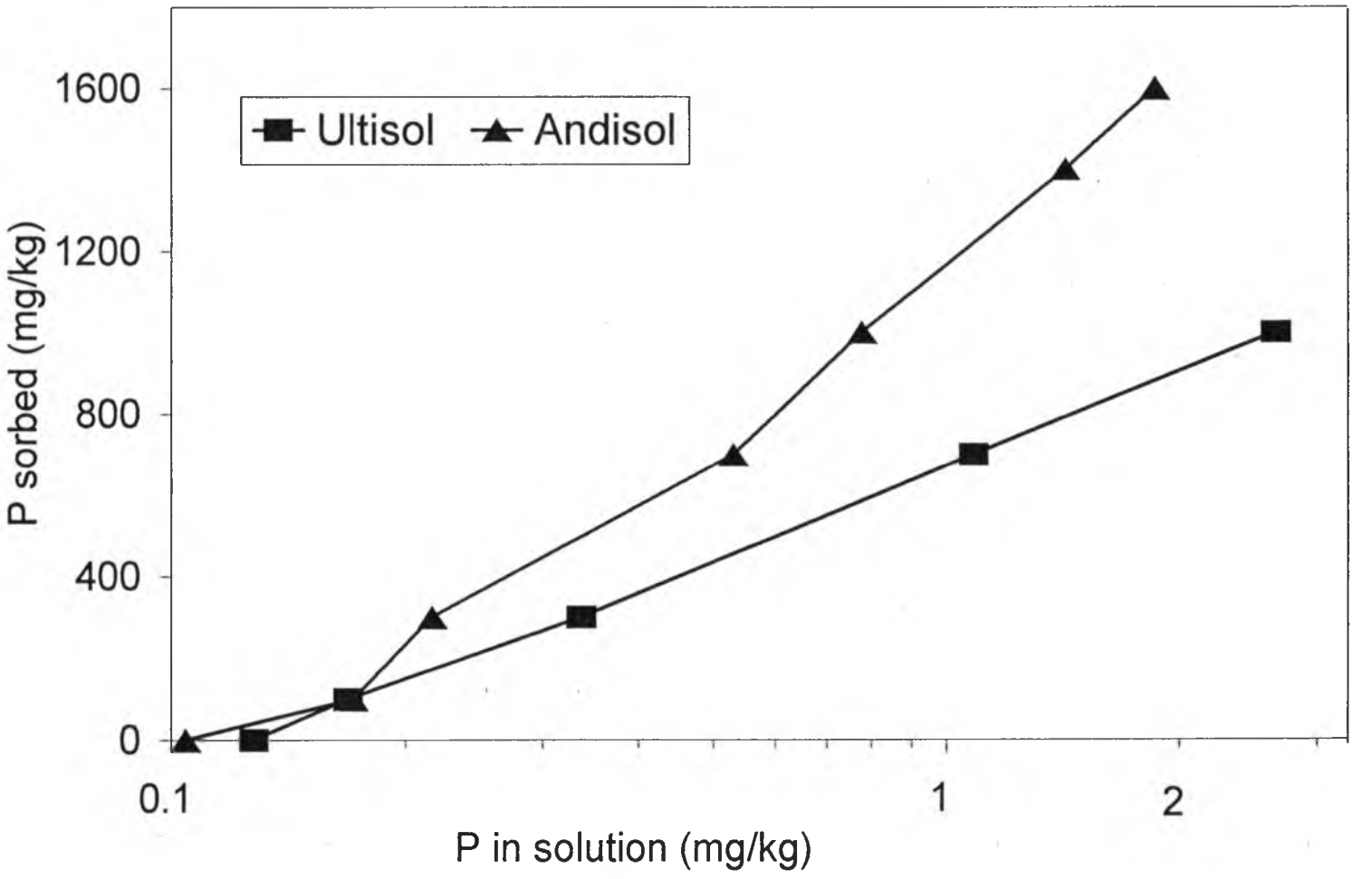

Fig. 1. P Sorption Isotherms for Soils Used in the Pot Trials.

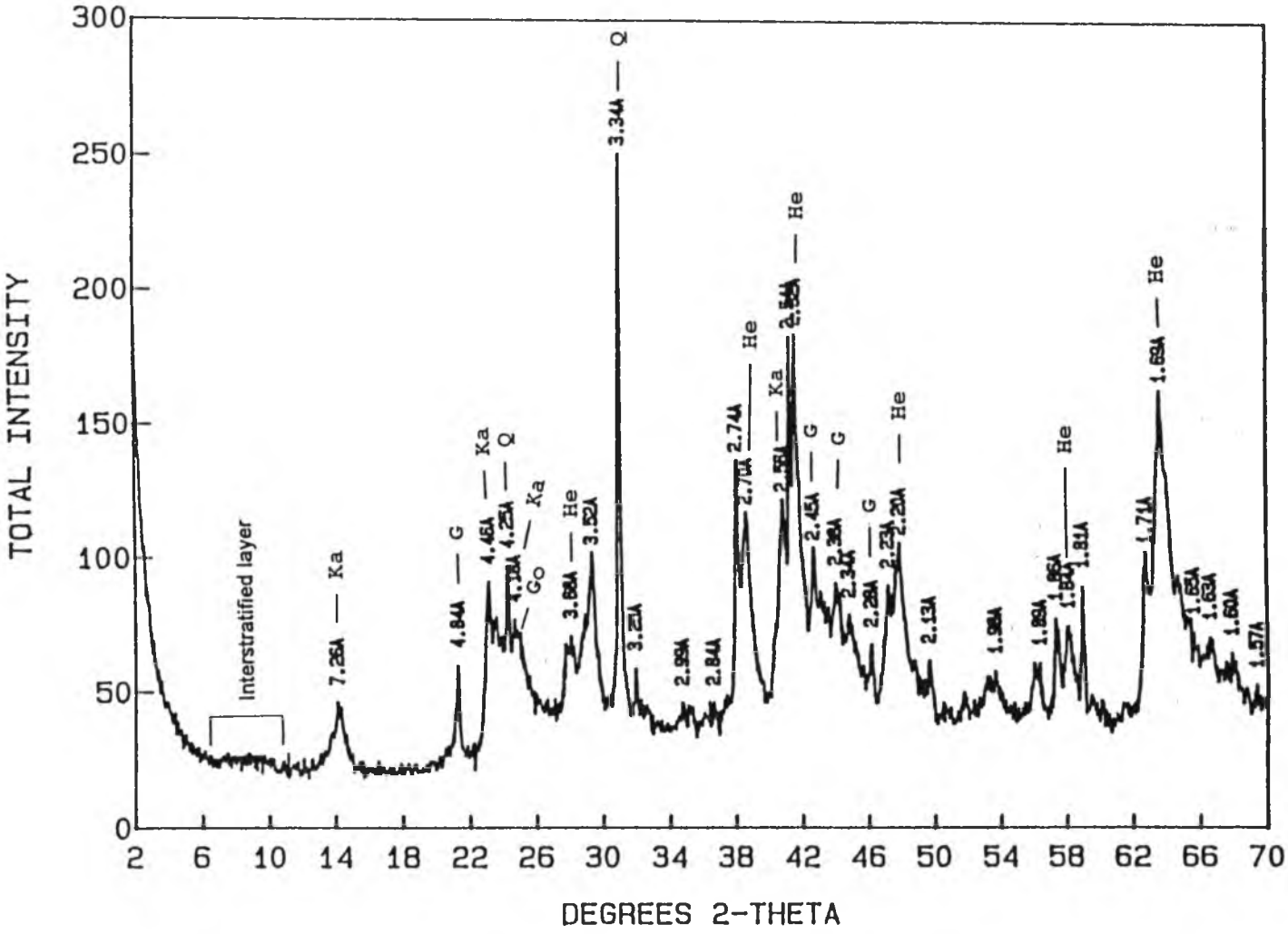

Fig. 2. X-ray Diffractogram of the Ultisol Showing Relative Amount of Kaolinite (Ka) and the Sesquioxides Hematite (He), Gibbsite (G), Goethite (Go). (Q = Quartz).

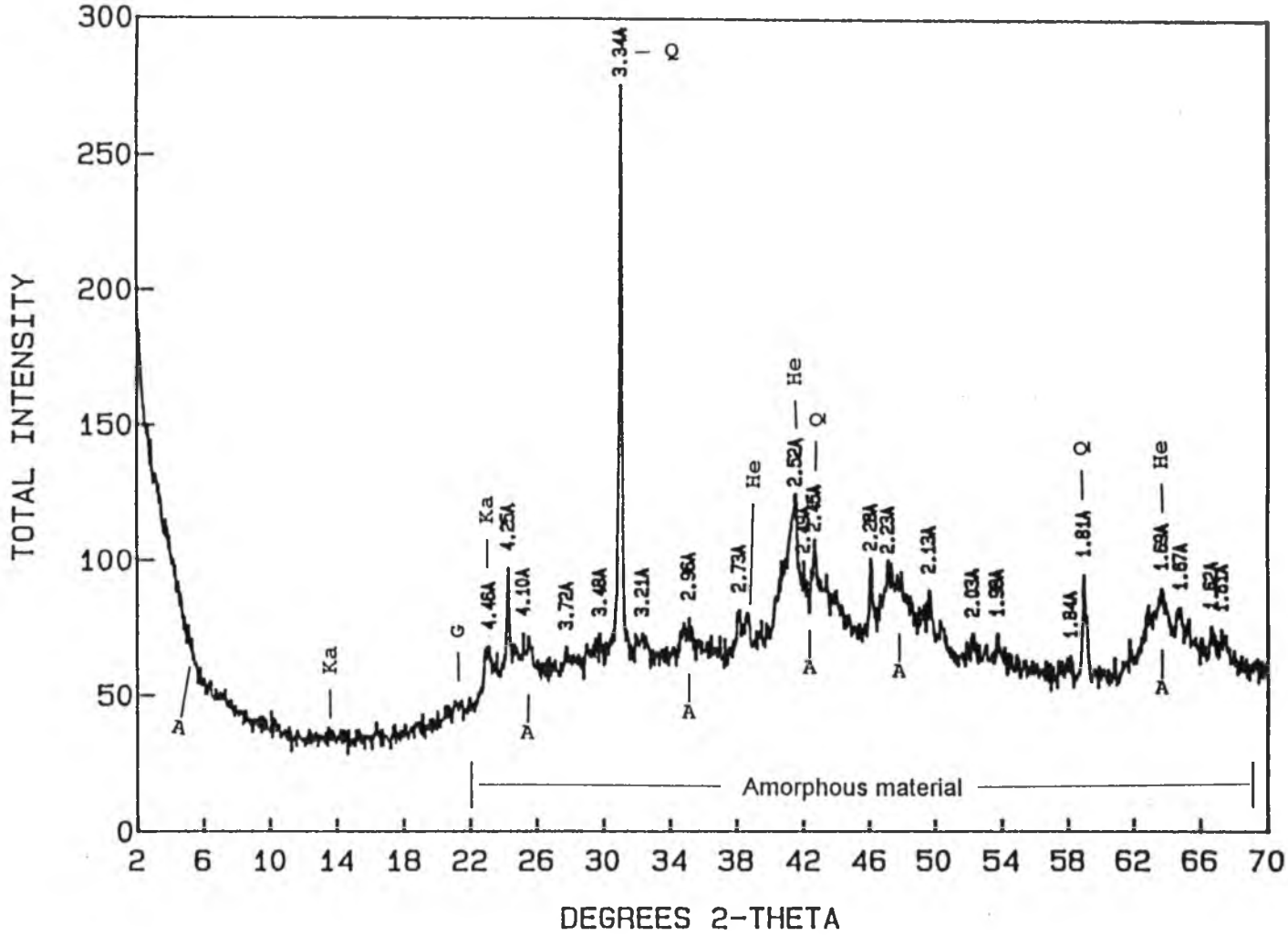

Fig. 3. X-ray Diffractogram of the Andisol Showing the High Content of Allophane (A) and Amorphous Material. (Q = Quartz).

applications. Bulk soil samples were collected from the A horizon (0-20 cm) of both soils. The Ultisol was air dried and the Andisol was kept moist. Both soils were ground to pass through a 6-mm sieve. Soils were limed to pH 6 by adding 2.2 g/kg of $Ca(OH)_2$ for the Leilehua soil and 3.7 g/kg for the Maile soil. Lime additions were based on a lime titration curve. Soils were then moistened to field capacity and incubated for two weeks. The vegetable crops used in this study were sweet corn (*Zea mays* cv. 'Hawaiian Supersweet #10A') and Chinese cabbage (*Brassica chinensis*, common name Wong Bok). Each crop was grown on each soil as a separate experiment. Thus four pot experiments are included in the study.

Fertilizer Treatments

After the two-week incubation period, P and K treatments were applied at rates determined using the Escobar 5^2 partial factorial treatment design, which permits an efficient estimation of fertilizer response surfaces (Laird and Turrent, 1981). This design provides 5 levels of application for both nutrients while reducing the total number of treatment combinations to 13 (as compared with 25 in the complete 5^2 factorial design). For each nutrient, the middle of the 5 levels is the estimated optimal application rate. This rate is then multiplied by 0.15, 0.6, 1.4, and 1.85 to obtain the other 4 application rates. A complete control (which received no fertilizer application) and a partial

control (which received the blanket fertilizer application as described below) were added to this treatment design for these experiments. (The treatment combinations expressed as Escobar codes are given in Table 4.)

For K, 150 kg/ha was selected as the optimal level in all four pot experiments. For each soil, a P-sorption curve (Fox and Kamprath, 1977) was used to determine the P addition required to obtain an optimal soil solution P concentration (Fig. 1). The optimum concentrations used for sweet corn were 0.05 and 0.06 mg P/L in the Leilehua and Maile soils, respectively, and 0.2 mg P/L for Chinese cabbage. These values were based on the levels suggested by Fox (1986) for these soil and crop types. Actual P and K application rates for the four pot experiments are given in Table 5. (P application rates reported here in units of kg/ha were adjusted for bulk density based on an assumed soil volume in the plow layer of 1500 m^3/ha for both soils.) All pots other than the complete controls received a blanket fertilizer application of N, Zn, Cu, B, Mg at rates of 200, 15, 10, 5, and 100 kg/ha, respectively, immediately before P and K were applied.

Greenhouse Experiments

The four pot experiments in this study were all conducted in the greenhouse located at the Department of Agronomy and Soil Science Mauka Campus. Two kilograms (oven dry basis) of the Ultisol and 1 kilogram (oven dry basis) of

Table 4. Treatments and Escobar codes

Treatment	Escobar code	
	P	K
A	-.85	-.85
B	-.85	+.85
C	+.85	-.85
D	+.85	+.85
E	-.40	-.40
F	-.40	+.40
G	+.40	-.40
H	+.40	+.40
J	0	0
K	-.85	0
L	+.85	0
M	0	-.85
N	0	+.85
O	-1	-1 (Complete control)
P	-1	-1 (Partial control)

Table 5. Actual Rates of P and K Used in the Four Pot Experiments.†

Escobar code	P applied (kg/ha) exp.1	exp.2	exp.3	exp.4	K applied (kg/ha)
+ 85	1382	2997	1041	2289	278
+ 40	1046	2268	788	1732	210
0	747	1620	563	1237	150
- 40	448	972	337	742	90
- 85	112	243	84	186	23

† Experiment 1 was sweet corn in the Ultisol; Experiment 2--Chinese cabbage in the Ultisol; Experiment 3--sweet corn in the Andisol; Experiment 4--Chinese cabbage in the Andisol. K application was the same for all trials. All treatments were applied on the soil weight bases.

the Andisol for each treatment were placed into a 2-kg pot. Less than 1 kg (0.71 kg--oven dry basis) of the Andisol was used for the Chinese cabbage trial due to a shortage of soil. Seeds were planted immediately after all required fertilizers had been mixed with the soils. Ten seeds of sweet corn or Chinese cabbage were planted in each pot. Pots were thinned to 4 plants for sweet corn and 5 plants for Chinese cabbage about ten days after emergence. Water was added each day to maintain the moisture at about field capacity. Experiments were installed in a randomized complete block design with 3 replications, which resulted in a total of 45 observations per experiment. Two additional treatments, 0 P + 150 kg/ha K and 0 K + 747 kg/ha P, were added to experiment 1 (the sweet corn-Leilehua combination). The two treatments with -0.40 K Escobar codes were removed from experiment 2 (the Chinese cabbage-Leilehua combination) because the K effect in the first experiment was very small. The 45 observations described above were used for experiment 3 (the sweet corn-Maile combination) and experiment 4 (the Chinese cabbage-Maile combination).

Plants were harvested by cutting the stems at ground level four weeks after planting. The height of sweet corn and the length of the longest leaf of Chinese cabbage were measured just before harvest. Plant samples were dried in an oven at 70°C for dry weight determination, and the samples were ground in a Stainless Steel Wiley Mill for chemical

analysis. Samples were analyzed for P, K and other nutrient content. Soil samples were collected after the harvest of each experiment. The Ultisol samples were air dried and the Andisol samples were kept moist in plastic sample bags. All soil samples used in nutrient analysis were first ground to pass through a 2-mm sieve.

Incubation Study

During a one-month pot study, soil K status can be markedly reduced by plant K uptake. To assess K status at planting, an incubation study was conducted. Eight 100-g samples of the Ultisol and seven 50-g samples of the Andisol (due to the limited amount of soil, only one sample was used in the control treatment for the Andisol) were mixed with 0.22 g and 0.185 g $Ca(OH)_2$, respectively, to adjust the pH to 6. Deionized water was added to bring the soils approximately to field capacity. Each soil sample was spread on a plastic sheet and placed in the green house. All the Ultisol samples were allowed to dry and then rewet with deionized water for six cycles, which were completed in one week. The Andisol samples were kept moist for one week. K applications of 0, 23, 150, and 278 kg/ha were applied to the soil samples after one week's incubation. Two replicates were used for each treatment other than the control in the Andisol, for which a single replicate was used. Ultisol samples were allowed to dry and then rewet with deionized water for three cycles and then kept moist for the rest of

the week (total incubation with K was one week). Andisol samples were kept moist for one week. All samples were ground to pass through a 2-mm sieve for K analysis.

Laboratory Analysis

Soil P extractants included Olsen (Olsen and Sommers, 1982), which is one of the most popular P extraction methods and is used by the Agricultural Diagnostic Service Center at the University of Hawaii for soil with pH > 7; Modified Truog (Ayres and Hagihara, 1952), which is used by the Agricultural Diagnostic Service Center at the University of Hawaii and by the Hawaiian Sugar Planter's Association Laboratory; Mehlich-III (Mehlich, 1984), which is a popular alternative method; and ion-exchange resin, using the modified method of Yang et al. (1990).

Mehlich-III was used to extract soil K from each soil in the main (3 X 3 factorial) treatment design and all samples from the incubation study. For one experiment with each soil, K was extracted with 1 *M* NH_4OAc at pH 7 (Thomas, 1982) from soils in the main (3 X 3 factorial) treatments and from all soil samples used in the incubation study. Values from these extractions served as the basis for comparison as this is the standard method for extracting soil cations. In these two experiments, the modified ion-exchange resin method was used for both P and K measurements in soil samples from the main (3 X 3 factorial) treatments in both soils and in Ultisol samples from the incubation study (because of the

shortage of the Andisol soil, the resin method was not used for the Andisol samples from the incubation study).

Because this study focused primarily on the identification of an alternative method for simultaneous extraction of P and K, rather than on the calibration of the methods for each crop in the study, only two methods, Modified Truog and Mehlich-III, out of the four P extraction methods mentioned above were chosen for soil samples collected from the two Chinese cabbage experiments. The Murphy and Riley reagent (1962) was used for determining soil P in soil extracts from Mehlich3, Modified Truog, and Olsen extraction methods. The absorbance was read within one hour after the Murphy and Riley reagent was added due to the observance of instability in the blue color developed in the Mehlich3 soil extracts after one hour. Amounts of P extracted by the resin method were determined with an Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES) because P concentrations in extracts from many treatments were too low to use the colorimetric method. Amounts of K extracted from Mehlich3, resin, and NH_4OAc were analyzed with atomic absorption spectrophotometry (AA).

Resin method procedures used in this study: a saturated paste was made by adding deionized water to a soil sample within a 100-ml plastic containers. The sample consisted of 50 g of the air-dried Ultisol soil or 50 g of the moist Andisol soil. A resin extractor (about 2.5 cm in diameter

and consisting of 5 mL of commercially available mixed H^+ and OH^- (1:1) exchange resin in a tight sphere held by polyester mesh cloth tied with polyester thread) purchased from E. O. Skogley was completely immersed in the center of the saturated paste. The container was covered with plastic film and the sample was allowed to equilibrate for three days at room temperature (25°C). The resin extractor was removed from the paste and washed with deionized water until the water was clear. The resin extractor was then placed in a 100 mL flask and 20 mL of 2 M HCl was added to the flask, the flask was covered with parafilm and shaken for 10 min. The solution was filtered through Whatman No. 40 or 42 filter paper into a 50 mL flask. The same extraction procedures were repeated two more times with 20 mL HCl used the second time and 10 mL HCl used the final time. Solutions from the three extractions were combined and mixed well for P and K determinations. All soil analyses were conducted in duplicate and the average of these two analyses was used for data analysis.

Plant samples were analyzed for P, K and other nutrients by the Agricultural Diagnostic Service Center of the University of Hawaii.

Data Analysis and Evaluation Methods

Statistical data analysis was performed on plant data and average values of soil test results from duplicate samples. SAS's PROC GLM CONTRAST (SAS Institute, 1985) was

performed to evaluate the effects of P and K application on plant dry matter yield, P and K uptake, P and K concentrations in plant tissue, plant height, and leaf length. The P and K effects on dry matter, P or K uptake, and tissue P or K were also illustrated with graphs of P or K application. The correlations between P applied, P extracted, and plant data and between K applied, K extracted, and plant data were evaluated by regression and graphic analysis. In order to compare the relationships between dry matter and P added or P extracted and K added or K extracted among trials, a single quadratic model, $Y = P + P^2 + K + K^2 + P*K$ (where Y is predicted dry matter yield, P is either P applied or P extracted, and K is either K applied or K extracted) was applied to data from each trial.

Correlation coefficients of test values with plant growth, dry matter yield, and plant nutrient uptake were one set of criteria used in assessing the potential of the P and K extraction methods for prediction of crop nutrient requirements. Other criteria used were the coefficients of variation for the sampling errors in each of the experiments, the sensitivity of test values to differences in soil P availability, and the accuracy of diagnoses based on critical ranges for extractable P that were derived for each of the methods. The last two of these criteria were based on estimates derived from the linear and plateau response model as described below. The ratios of P and K extracted to P and

K applied were also used as the measurements for sensitivity of the P and K test to changes of P and K availability in soil. Finally, the efficiency of the methods for laboratory operations was also considered.

Both the linear plateau model (Cox, 1992) and the quadratic model were used to estimate the critical extractable P levels for all P extraction methods tested in the Chinese cabbage trials and in the sweet corn trial on the Ultisol. For the sweet corn trial on the Andisol, the response of dry matter yield to P applications was approximately linear across P range tested. Therefore, we were not able to estimate the critical P levels for this trial using either of the models. Critical P levels were estimated at the inflection point for the linear plateau model and at 85% of the maximum predicted dry matter yield for the quadratic model. Relative yields (as percentages of the maximum yield at each K level for which a yield plateau was obtained) were used in fitting these models. Although values of 90 or 95% of maximum yield are more commonly selected in establishing critical levels (Black, 1993), 85% was chosen in this study to compensate for the higher P requirements of young crops. The percentage of the maximum dry matter yield chosen as the target yield in this study was based on the percentages suggested by Fox (1986) and the consideration that young crops usually have much higher critical levels than mature crops. It was concluded that a

level of 85% of maximum dry matter yield for young crops should be adequate.

The linear plateau model was fit in SAS using PROC NLIN (SAS Institute, 1985). Estimates from the fitted models were used to evaluate P extraction methods in three ways.

In one method, the reciprocals of the estimated slopes from these fitted models were used as measures of the sensitivity of each method's test values to soil P levels.

In another method, a critical range for each P extraction method in each trial was obtained using the 95% confidence interval for the predicted critical P levels. These critical ranges and the 95% confidence interval for the predicted yield plateau were used to assess the accuracy of diagnoses of insufficient soil P levels in three experiments. Each soil P test value obtained in these experiments was classified as falling below, within, or above the critical range. The accuracy of the methods was evaluated based on the numbers of correct and incorrect diagnoses. Soil P test values were considered "incorrect diagnoses" if they fell in the area where dry matter yields were significantly below the yield plateau and P test values were above the critical range and where dry matter yields were not significantly below the yield plateau and P test values were below the critical range. Soil P test values were considered "correct diagnoses" if they fell in the area where dry matter yields were significantly below the yield plateau and P test values

were below the critical range and where dry matter yields were not significantly below the yield plateau and P test values were above the critical range. No assessment of the accuracy of diagnoses was made where P test values were within the critical range because these values are not significantly above or below the critical P level.

The third method used the ratio between the critical range and the range in measured soil P test values as a measure of the accuracy of diagnoses. The difference between the upper and lower 10th percentile test values was used as the denominator in calculating this ratio. A high value for this ratio means there is a wide range of soil P levels for which diagnosis is uncertain and therefore indicates low precision for the method.

Critical levels for K were estimated only with the quadratic model because reliable estimates could not be obtained with the linear plateau model.

CHAPTER 4

RESULTS AND DISCUSSION

Effects of Fertilizer Applications

Application of P and K significantly increased ('PK vs. No' column in Tables 6, 7, 8, and 9) dry matter, plant height of sweet corn or leaf length of Chinese cabbage, P and K uptake, and tissue P concentration of both sweet corn and Chinese cabbage in both the Ultisol and the Andisol (Appendixes A-F). Comparing the partial control treatment to the treatments with P and K application, on average, tissue K concentration was significantly lower in the partial control treatments in all cases other than in sweet corn when grown on the Ultisol, where there was a significant decrease in tissue K with P and K fertilization. Probability levels for these effects are given in Tables 6, 7, 8, and 9 in the rows labeled 'PK vs No'.

EFFECT OF P APPLICATION ON SWEET CORN

There were curvilinear responses of sweet corn dry matter and height to P application in the Ultisol (Figs. 4 and 5). For sweet corn on the Andisol, the response of dry matter (R^2 = 0.83) was more linear than that on the Ultisol (Figs. 4 and 6); however, the response of plant height to P application was very similar (R^2 = 0.92) to that on the Ultisol (Figs. 5 and 7). This indicated that sweet corn dry matter had not reached a plateau on the Andisol. P application greatly increased P and K uptake, and plant

Table 6. Probability† from F Tests for Effects of P and K Applications on Sweet Corn Growth and Nutrient Status in the Ultisol.

Contrast	DM	Height	Tissue P	P uptake	Tissue K	K uptake
PK vs No	0.0001	0.0001	0.0002	0.0001	0.0158	0.0001
P-linear	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
P-quad	0.0001	0.0001	0.7406	0.5475	0.0001	0.1785
K-linear	0.0012	0.2903	0.5779	0.5913	0.0003	0.0001
K-quad	0.8850	0.4616	0.6102	0.3504	0.9168	0.3023
Pl*Kl	0.0811	0.4740	0.4721	0.8782	0.5775	0.0018
Pl*Kq	0.1250	0.3123	0.9439	0.3510	0.6410	0.2669
Pq*Kl	0.0103	0.0272	0.9400	0.2453	0.8826	0.0073
Pq*Kq	0.0732	0.3983	0.7343	0.7749	0.3860	0.1760

† Probability of obtaining an F value greater than that observed.

Table 7. Probability† from F Tests for Effects of P and K Applications on Sweet Corn Growth and Nutrient Status in the Andisol.

Contrast	DM	Height	Tissue P	P uptake	Tissue K	K uptake
PK vs No	0.0001	0.0001	0.0001	0.0006	0.0254	0.0001
P-linear	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
P-quad.	0.7571	0.0001	0.0398	0.2694	0.5878	0.0002
K-linear	0.1133	0.0526	0.0467	0.0273	0.0001	0.0001
K-quad.	0.2437	0.5986	0.0398	0.6045	0.6282	0.3641
Pl*Kl	0.3126	0.7797	0.3012	0.1093	0.7560	0.0001
Pl*Kq	0.1304	0.3210	1.0000	0.2831	0.3072	0.7218
Pq*Kl	0.4106	0.2381	0.2357	0.6327	0.7858	0.0086
Pq*Kq	0.5774	0.4468	0.3012	0.3922	0.7470	0.7739

† Probability of obtaining an F value greater than that observed.

Table 8. Probability† from F Tests for Effects of P and K Applications on Chinese Cabbage Growth and Nutrient Status in the Ultisol.

Contrast	DM	Length	Tissue P	P uptake	Tissue K	K uptake
PK vs No	0.0001	0.0001	0.0001	0.0005	0.0023	0.0188
P-linear	0.0001	0.0001	0.0001	0.0001	0.2769	0.0003
P-quad	0.0001	0.0001	0.0005	0.0017	0.0721	0.0626
K-linear	0.6079	0.4981	0.0001	0.0087	0.0171	0.8740
K-quad	0.5145	0.7871	0.0001	0.0003	0.0095	0.8015
Pl*Kl	0.3700	0.8602	0.0001	0.0007	0.3572	0.0222
Pl*Kq	0.9801	0.7847	0.0002	0.0517	0.0152	0.7433
Pq*Kl	0.1277	0.5326	0.0001	0.0005	0.0128	0.3139
Pq*Kq	0.2687	0.4462	0.0507	0.3533	0.5023	0.3484

† Probability of obtaining an F value greater than that observed.

Table 9. Probability† from F Tests for Effects of P and K Applications on Chinese Cabbage Growth and Nutrient Status in the Andisol.

Contrast	DM	Height	Tissue P	P uptake	Tissue K	K uptake
PK vs No	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
P-linear	0.0001	0.0001	0.0001	0.0001	0.0001	0.0306
P-quad.	0.0001	0.0001	0.0001	0.0001	0.0003	0.0201
K-linear	0.0001	0.0062	0.0115	0.0030	0.0001	0.0001
K-quad.	0.2515	0.1640	0.7666	0.0700	0.0307	0.5334
Pl*Kl	0.4509	0.5487	0.0529	0.5006	0.0034	0.6083
Pl*Kq	0.0113	0.0451	1.0000	0.2132	0.0049	0.9178
Pq*Kl	0.6105	1.0000	0.8084	0.3273	0.2449	0.2658
Pq*Kq	0.0169	0.8411	0.4073	0.0436	0.0380	0.5963

† Probability of obtaining an F value greater than that observed.

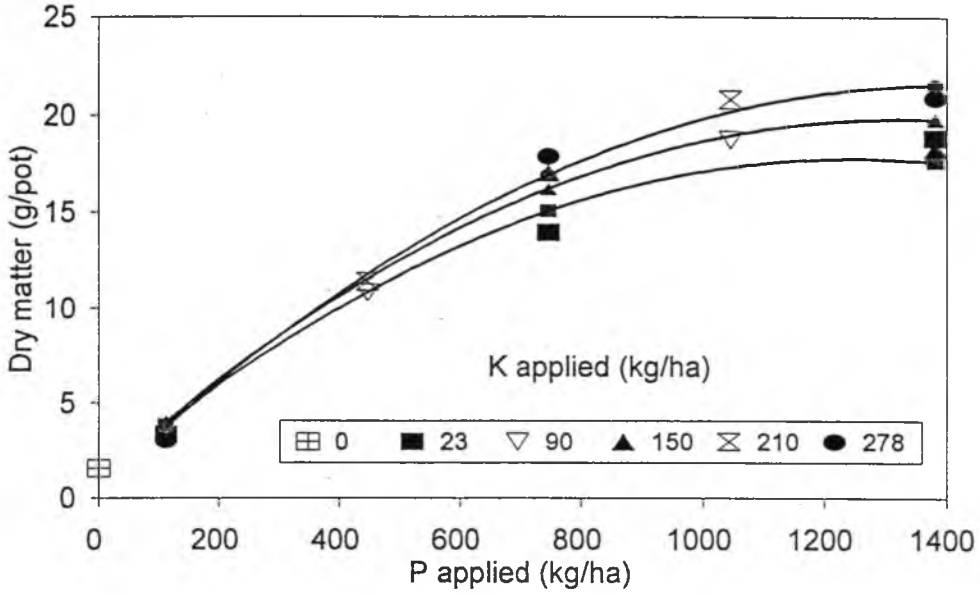

Fig. 4. Response of Sweet Corn Dry Matter Yield to P Applications in an Ultisol. (The regression equations for all major relationships are given in Appendix G.)

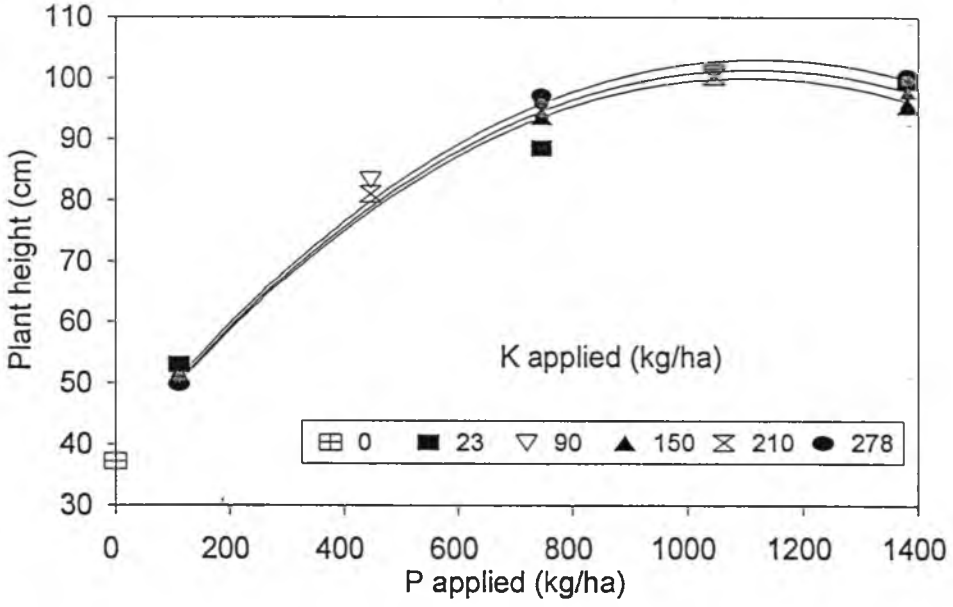

Fig. 5. Response of Sweet Corn Height to P Applications in an Ultisol.

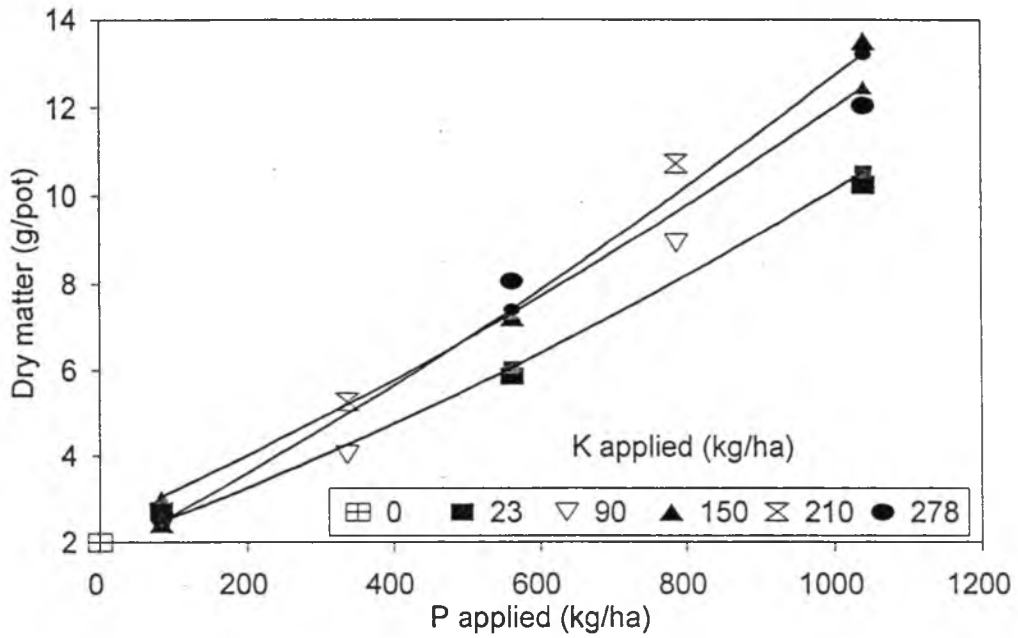

Fig. 6. Response of Sweet Corn Dry Matter Yield to P Applications in an Andisol.

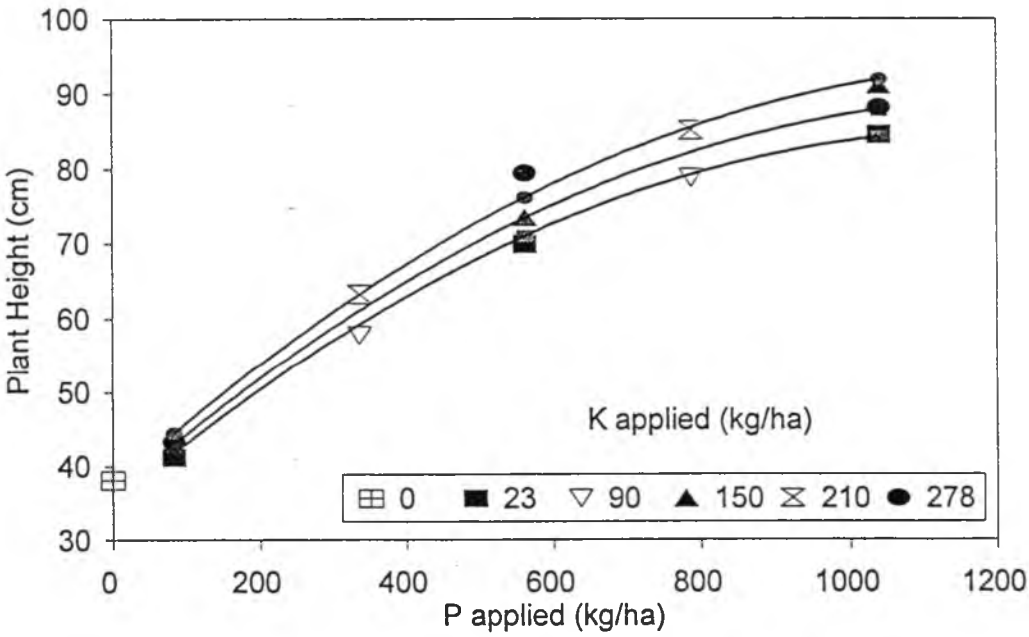

Fig. 7. Response of Sweet Corn Height to P Applications in an Andisol.

tissue P in both the Ultisol and Andisol (Appendixes A-D). The probabilities of these effects are shown in Tables 6 and 7. The linear responses of P uptake and plant tissue P concentration are also shown in Figs. 8 and 9. Dry matter increased 489% (averaged across K levels) in the Ultisol and 364% in the Andisol from the lowest to the highest P application rates. P and K uptake increased 1634% and 79%, respectively, in the Ultisol and increased 928% and 132%, respectively, in the Andisol from the lowest to highest P application rates.

P application seems to have had a strong dilution effect on tissue K in both soils, with a decrease of 70% in the Ultisol and 51% in the Andisol from the lowest to highest P application rates. The pattern of the P effect on tissue K was similar in the two soils (Figs. 10 and 11).

Dry matter, plant height, tissue P, and P uptake were generally higher in the Ultisol than in the Andisol. This might have been caused by a higher ratio of plant to soil in the Andisol trial.

EFFECT OF P APPLICATION ON CHINESE CABBAGE

P application greatly increased the dry matter, leaf length, P uptake, K uptake, and tissue P concentration of Chinese cabbage in both soils (Tables 8 and 9; Figs. 12-17). Dry matter increased 586% in the Ultisol and 45% in the Andisol from the lowest to the highest P application rates. The greatest increase in dry matter occurred between the

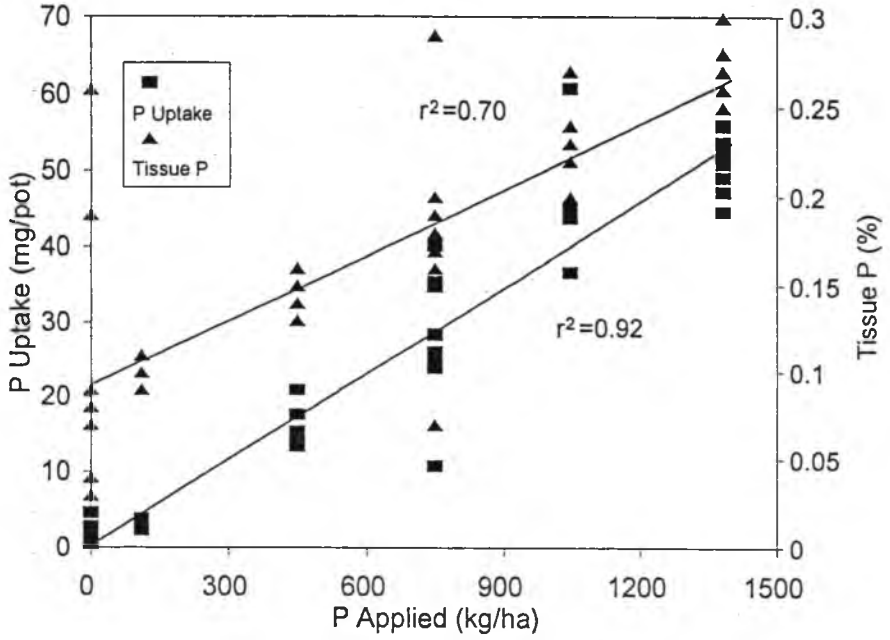

Fig. 8. Effect of P Applications on the P Uptake and Tissue P Concentration of Sweet Corn in an Ultisol.

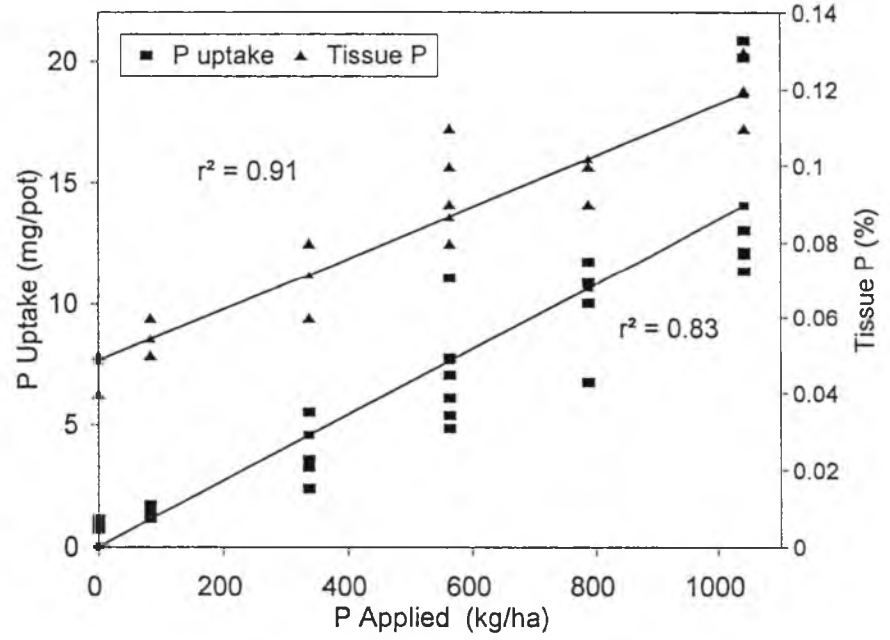

Fig. 9. Effect of P Applications on the P Uptake and Tissue P Concentration of Sweet Corn in an Andisol.

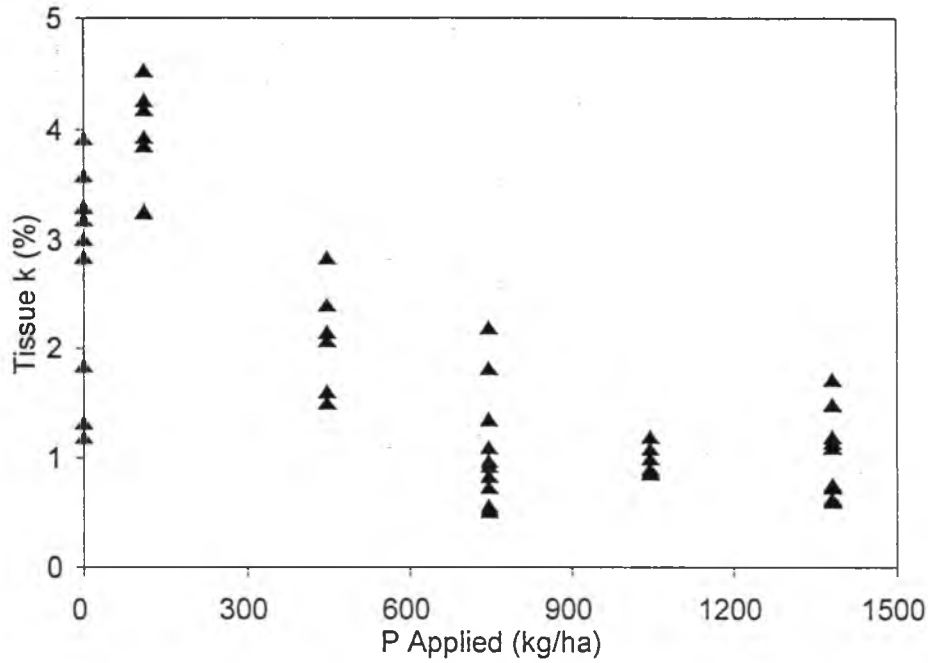

Fig. 10. Effect of P Applications on Sweet Corn Tissue K Concentration in an Ultisol.

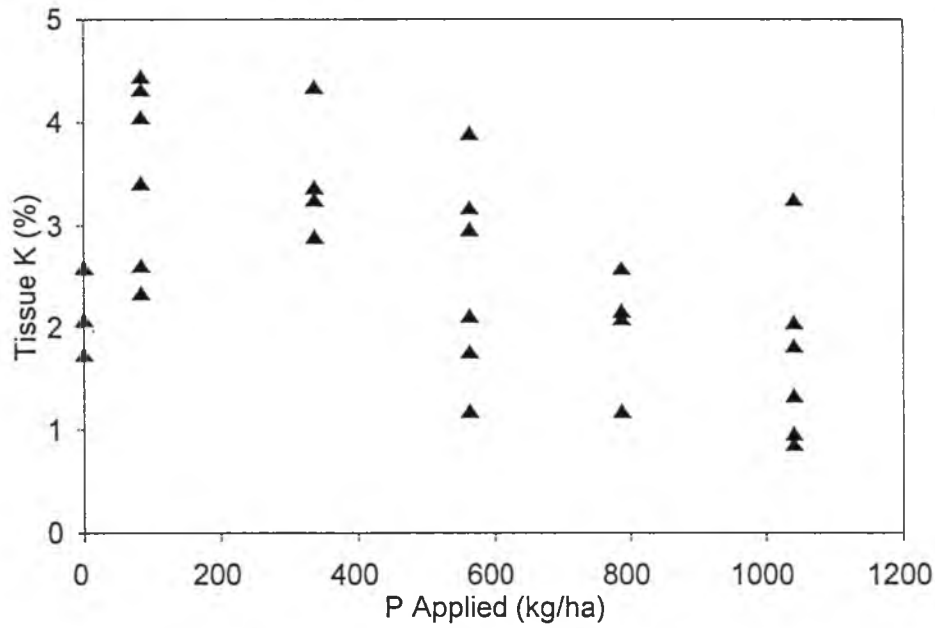

Fig. 11. Effect of P Applications on Sweet Corn Tissue K Concentration in an Andisol.

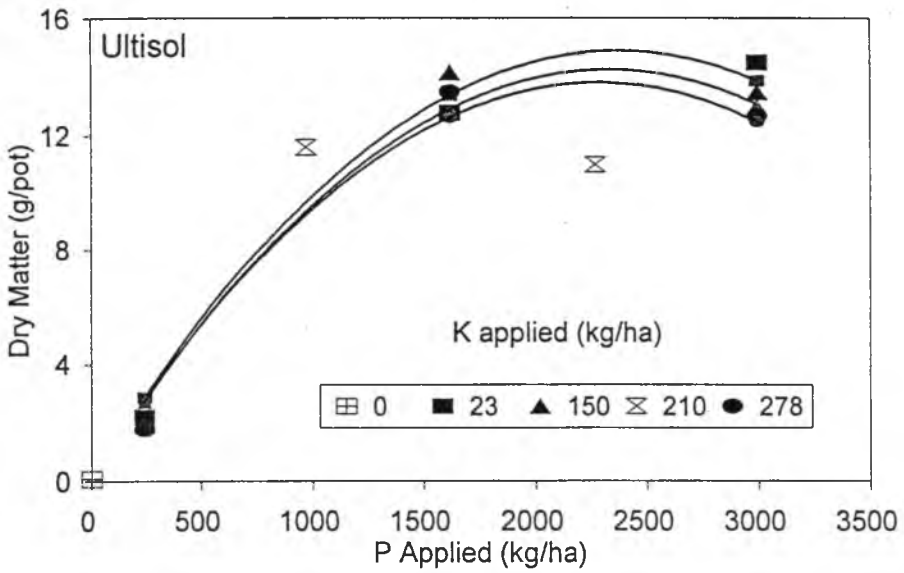

Fig. 12. Response of Chinese Cabbage Dry Matter Yield to P Applications in an Ultisol.

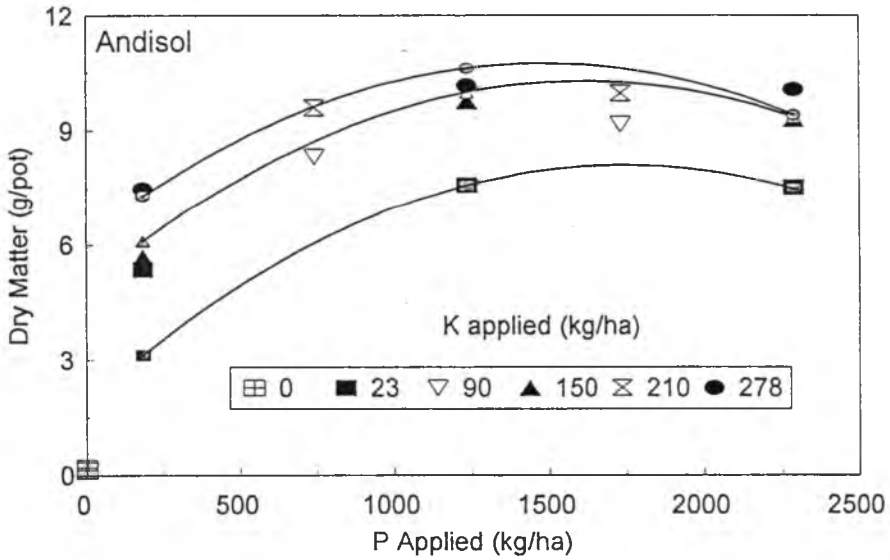

Fig. 13. Response of Chinese Cabbage Dry Matter Yield to P Applications in an Andisol.

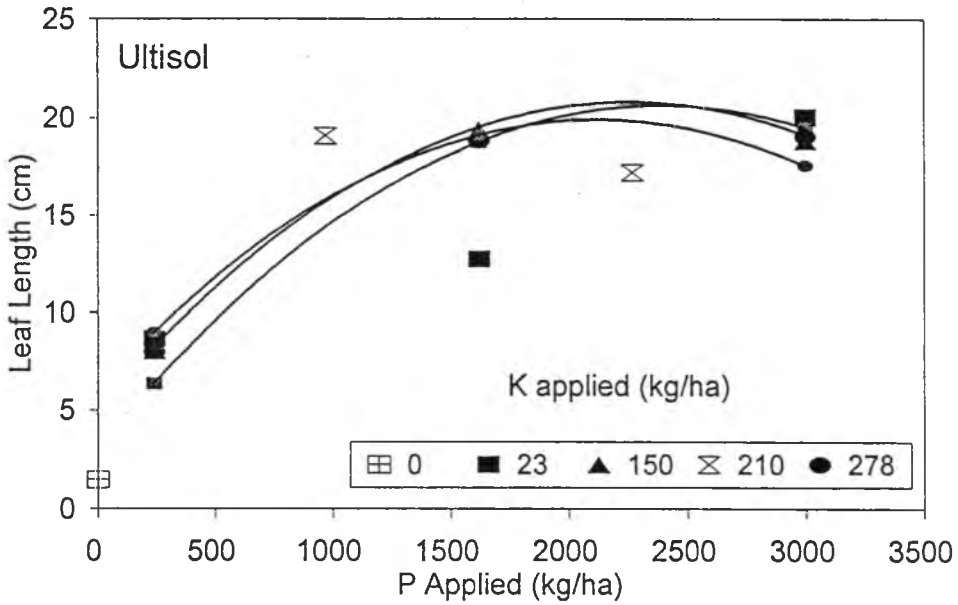

Fig. 14. Response of Chinese Cabbage Leaf Length to P Applications in an Ultisol.

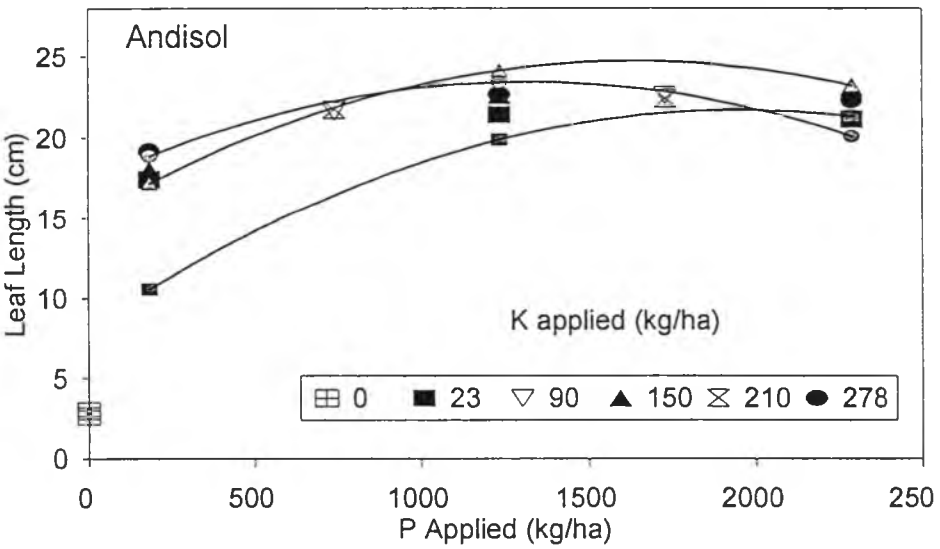

Fig. 15. Response of Chinese Cabbage Leaf Length to P Applications in an Andisol.

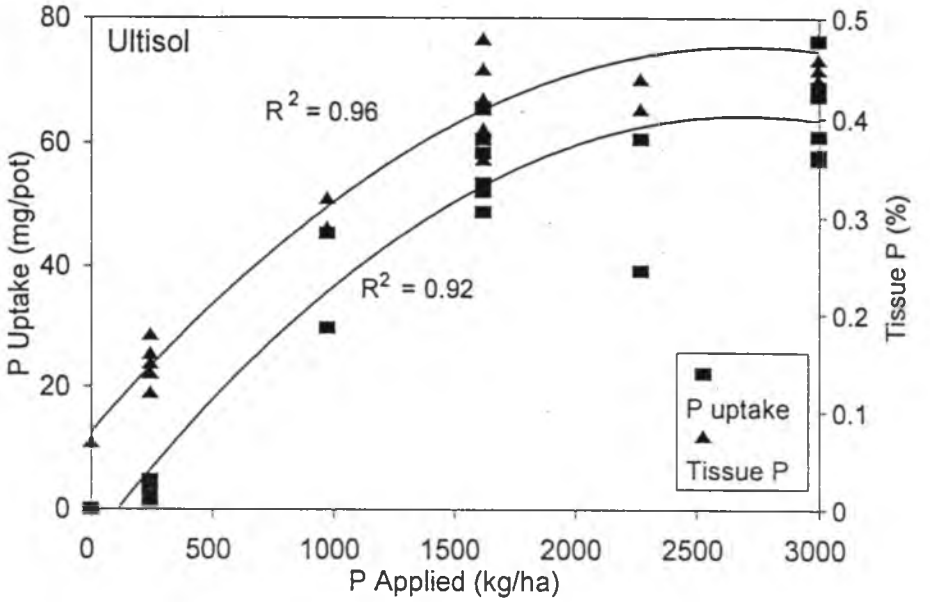

Fig. 16. Effect of P Applications on the P Uptake and Tissue P Concentration of Chinese Cabbage in an Ultisol.

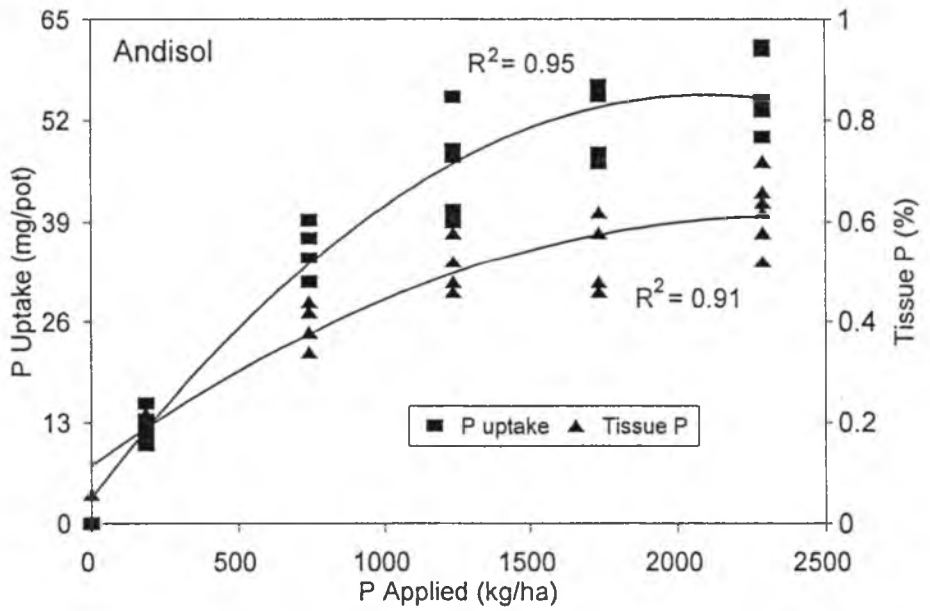

Fig. 17. Effect of P Applications on the P Uptake and Chinese Cabbage Tissue P Concentration in an Andisol.

first (243 kg/ha) and second (972 kg/ha) levels of P application in the Ultisol while the greatest dry matter increase occurred between the control and the first level of P application (186 kg/ha) in the Andisol (Figs. 12 and 13). The high P levels selected for the Chinese cabbage experiment seem too high in both soils, especially in the Andisol. The responses of tissue P and P uptake to P applications were very similar in the two soils. However, P uptake was generally higher in the Ultisol than in the Andisol due to higher dry matter production, while tissue P was generally lower in the Ultisol (Figs. 16 and 17). This might be the result of a difference in temperature between the two experiments as Chinese cabbage was grown in the summer on the Ultisol and in the fall on the Andisol. For the three highest P levels, the mean growth rates of Chinese cabbage ranged from 0.367-0.483 g/day/pot in the Ultisol compared to 0.238-0.318 g/day/pot in the Andisol while the mean rates for P uptake ranged from 1.55-2.45 mg/day/pot in the Ultisol and from 1.24-1.84 mg/day/pot in the Andisol. As P was not limiting at these levels, the lower tissue P concentrations in the Ultisol could have resulted from a dilution effect at the higher growth rates. P application had a greater dilution effect on tissue K in Chinese cabbage on the Ultisol (Fig. 18) than on the Andisol which showed no pattern of dilution effect. From the lowest (243 kg/ha in the Ultisol and 186 kg/ha in the Andisol) to the highest P rate (2997

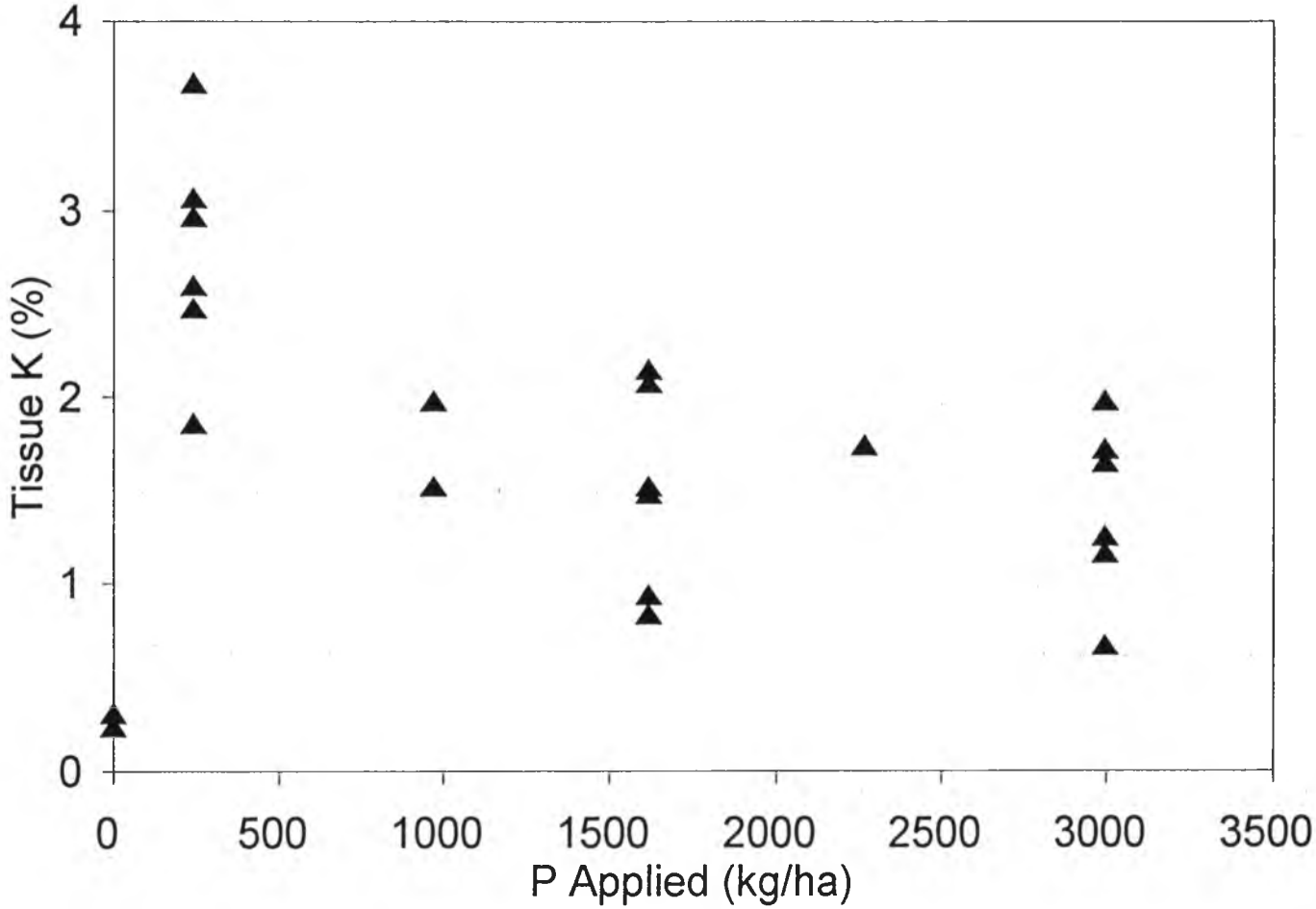

Fig. 18. Effect of P Applications on Chinese Cabbage Tissue K Concentration in an Ultisol.

kg/ha in Ultisol and 2289 kg/ha in Andisol), average tissue K (averaged across K levels) decreased 44.2% in the Ultisol and 22.4% in the Andisol. This difference can be attributed to the greater dry matter response to P on the Ultisol relative to that on the Andisol.

EFFECT OF K APPLICATION ON SWEET CORN

Potassium was not as limiting for sweet corn growth as P in either soil. The effect of K application on dry matter and K uptake occurred mainly at the higher P levels in both soils (Figs. 19, 20, 21, and 22). For example, at the lowest P application rates (112 kg/ha for the Ultisol and 84 kg/ha for the Andisol), there was almost no increase in dry matter (Figs. 19 and 20) and only a small increase in K uptake due to K application (Figs. 21 and 22). At higher P application rates, there were responses of plant dry matter yield to K application. On the Ultisol, the increases were 28% and 11%, respectively, at 747 and 1382 kg P/ha. On the Andisol, dry matter increased by 37% and 18%, respectively, at 536 and 1041 kg P/ha. Sweet corn dry matter increased significantly with K application on the Ultisol (Table 6). However, there was no significant response on the Andisol (Table 7). Higher variation in dry matter in the Andisol experiment may have caused the test of a K effect to be less powerful in this experiment than in the Ultisol experiment.

Potassium uptake and tissue K exhibited linear responses to K application in both soils (Tables 6 and 7). Responses

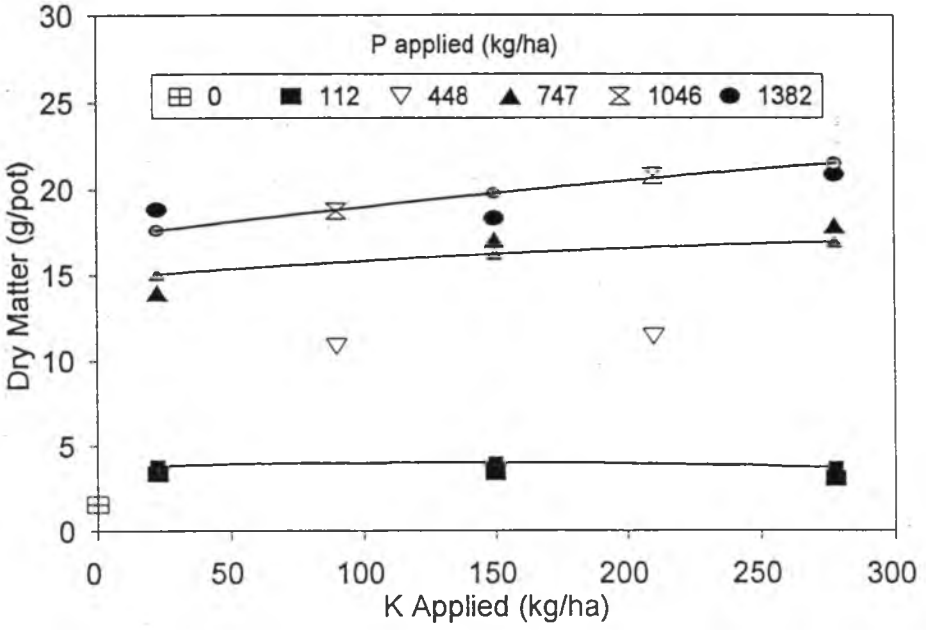

Fig. 19. Response of Sweet Corn Dry Matter Yield to K Appiications in an Ultisol.

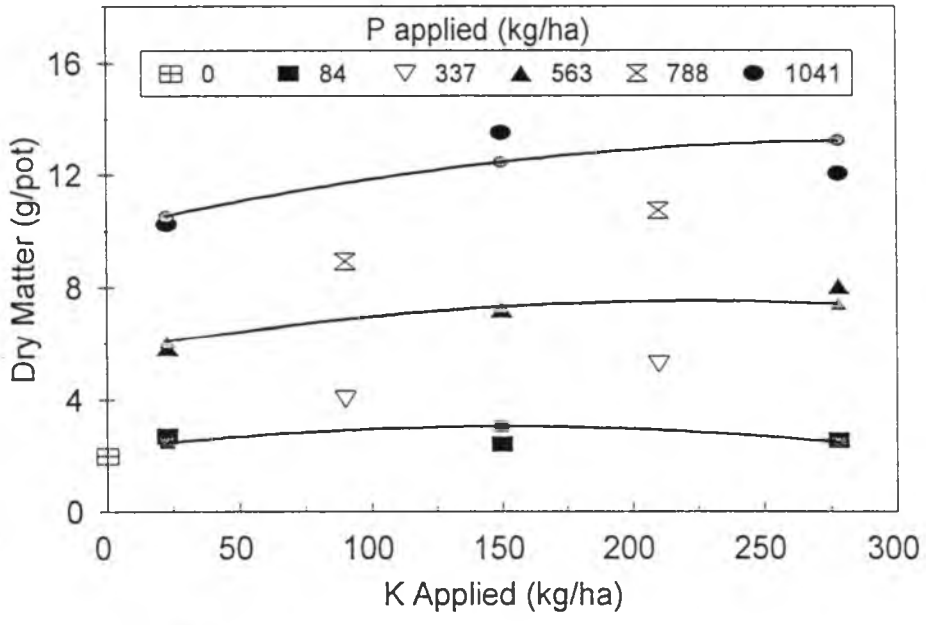

Fig. 20. Response of Sweet Corn Dry Matter Yield to K Applications in an Andisol.

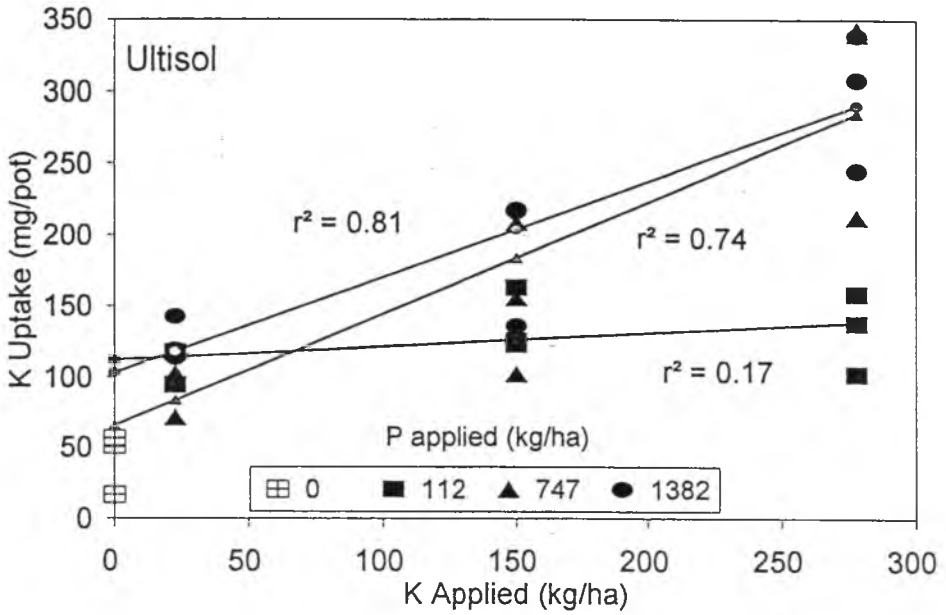

Fig. 21. Effect of K Applications on Sweet Corn K Uptake in an Ultisol.

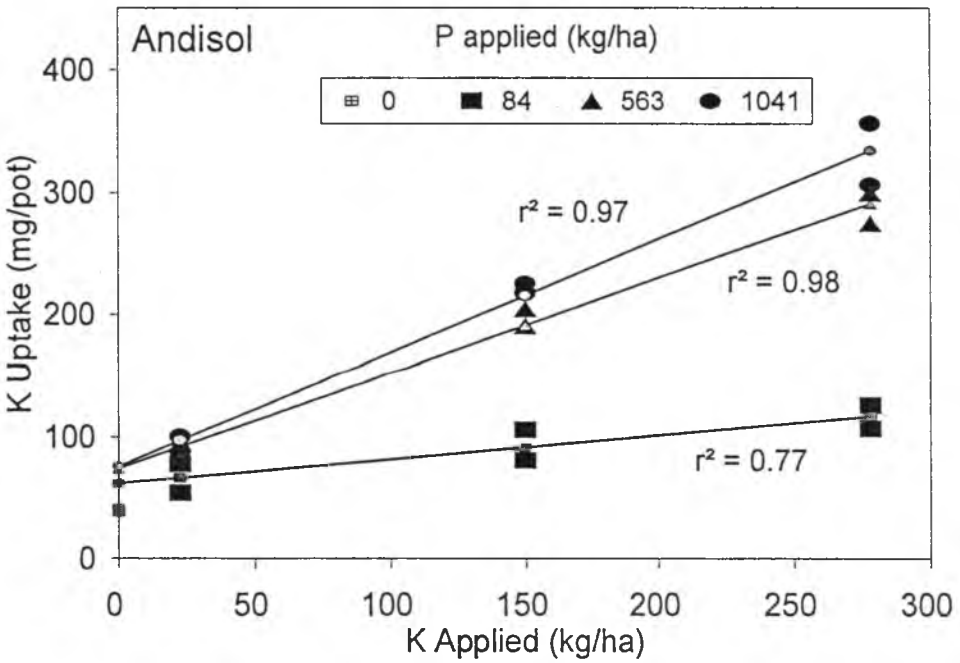

Fig. 22. Effect of K Applications on Sweet Corn K Uptake in an Andisol.

of K uptake at higher P levels were substantial, with increases of 212% and 140% at 747 kg P/ha and 1382 kg P/ha, respectively, for the Ultisol, and increases of 219% and 239% at 536 kg P/ha and 1041 kg P/ha for the Andisol. Regression analysis also showed a strong relation between K uptake and K applied at higher P levels, with r^2 values of 0.74 and 0.81 at 747 and 1382 kg P/ha, respectively, in the Ultisol, and r^2 values of 0.98 and 0.97 at 563 and 1041 kg P/ha, respectively, in the Andisol (Figs. 21 and 22). In both soils, the effect of K application on tissue K appears to vary less with different P levels than does the effect of K applied on K uptake (Figs. 23 and 24). However, slightly different patterns were obtained on the two soils, which might be caused by the dilution effect of P application on tissue K. In the Ultisol, this dilution effect appeared to have reached a maximum at 747 kg P/ha, but it did not appear to have reached a maximum in the Andisol (Figs. 23 and 24).

There were also linear responses of tissue P and P uptake to K application in the Andisol, with a 5% increase in tissue P and a 34% increase in P uptake from the lowest K level (23 kg/ha) to the highest K level (278 kg/ha). There was no significant response of tissue P or P uptake to K application in the Ultisol (Table 6). It seems that K had a greater effect on sweet corn in the Andisol than in the Ultisol, which could have resulted from the use of less soil and thus less total K per pot for the Andisol.

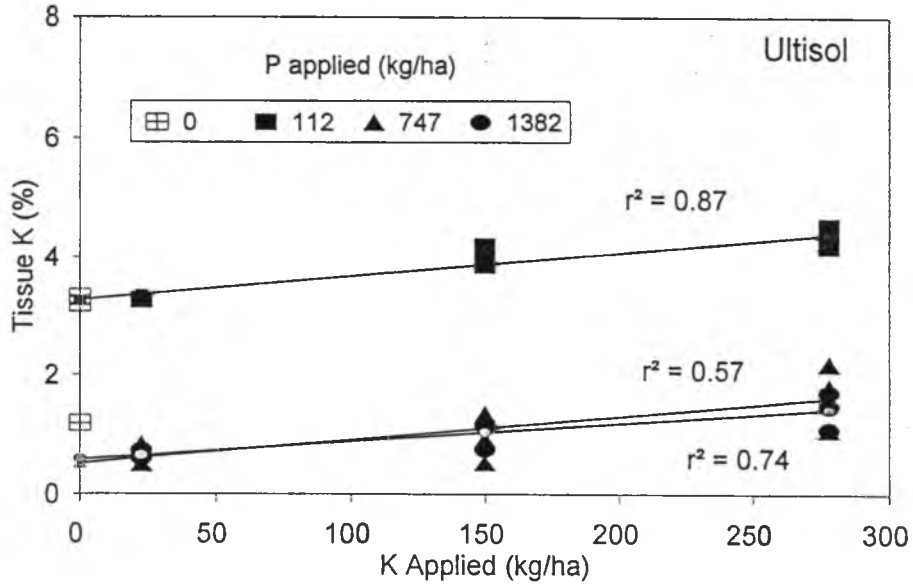

Fig. 23. Effect of K Applications on Sweet Corn Tissue K Concentration in an Ultisol.

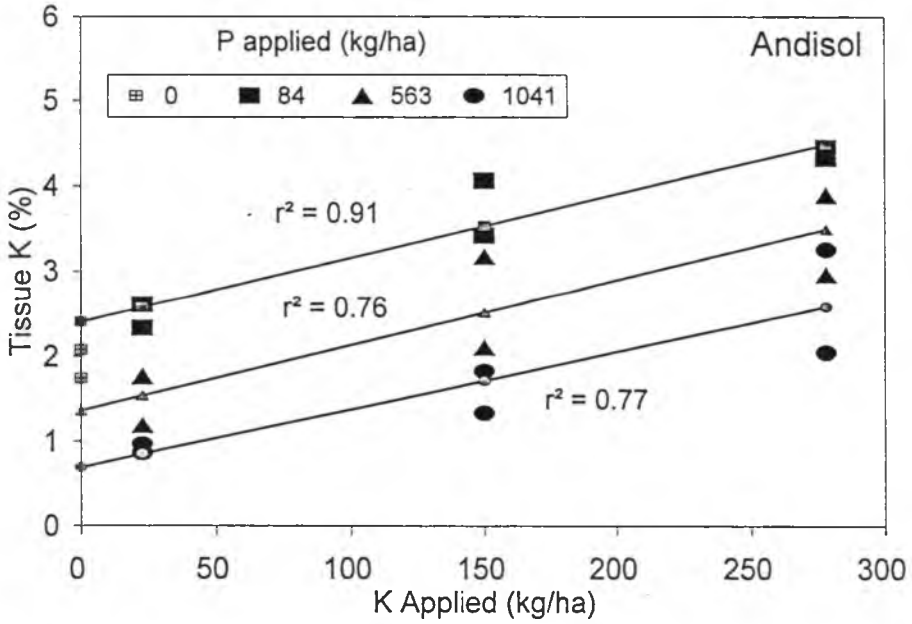

Fig. 24. Effect of K Applications on Sweet Corn Tissue K Concentration in an Andisol.

EFFECT OF K APPLICATION ON CHINESE CABBAGE

In the Ultisol, only tissue P, P uptake, and tissue K responded to K application (Table 8; Figs. 25, 26, and 27). In the Andisol, there were linear responses of dry matter, leaf length, tissue P, tissue K, P uptake, and K uptake to K application (Table 9; Figs. 28 and 29). Dry matter production (averaged across P levels) was 35% higher at 278 kg K/ha than at 23 kg K/ha in the Andisol, while dry matter yield remained basically the same across P levels in the Ultisol.

There were strong linear correlations between tissue K and K application at the higher P levels in the Ultisol (r^2 = 0.99 and 0.96 for P applications of 1620 and 2997 kg/ha, respectively). K uptake was also highly correlated with K application at higher P levels in the Ultisol, with r^2 = 0.94 and 0.84 for P applications of 1620 and 2997 kg/ha, respectively (Figs. 26 and 27). In the Andisol, tissue K and K uptake were highly correlated with K application at all levels of P, with r^2 = 0.90 and 0.97, respectively (Fig. 29). At the lowest level of P application (243 kg/ha) in the Ultisol, the poor correlation between K uptake and K applied might have been due to the poor plant growth with inadequate P that affected nutrient uptake. At the lowest level of K application, 23 kg/ha, both tissue K and K uptake were generally all lower in the Andisol than in the Ultisol. This might have been caused by less K being available in the

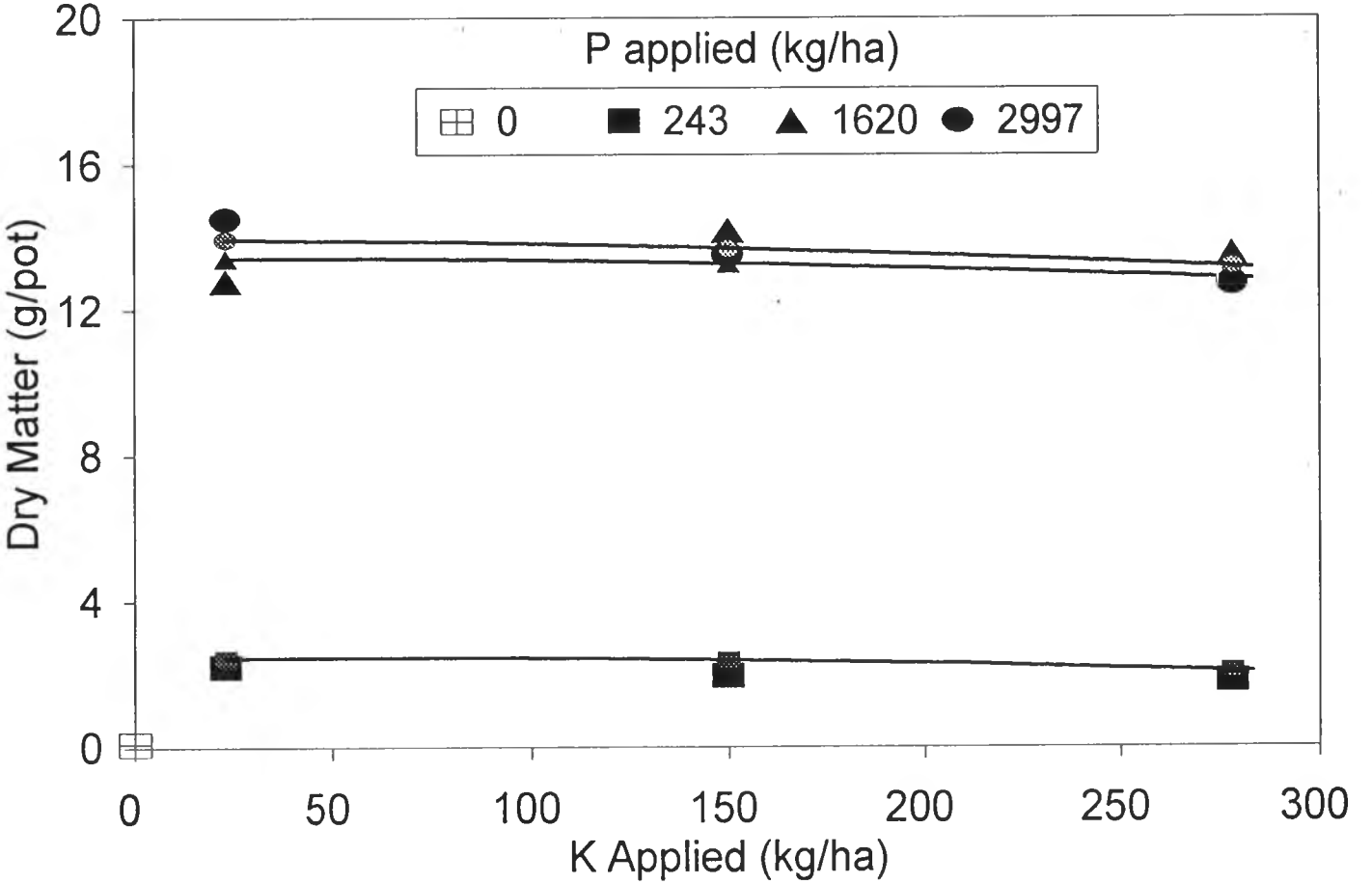

Fig. 25. Response of Chinese Cabbage Dry Matter Yield to K Applications in an Ultisol.

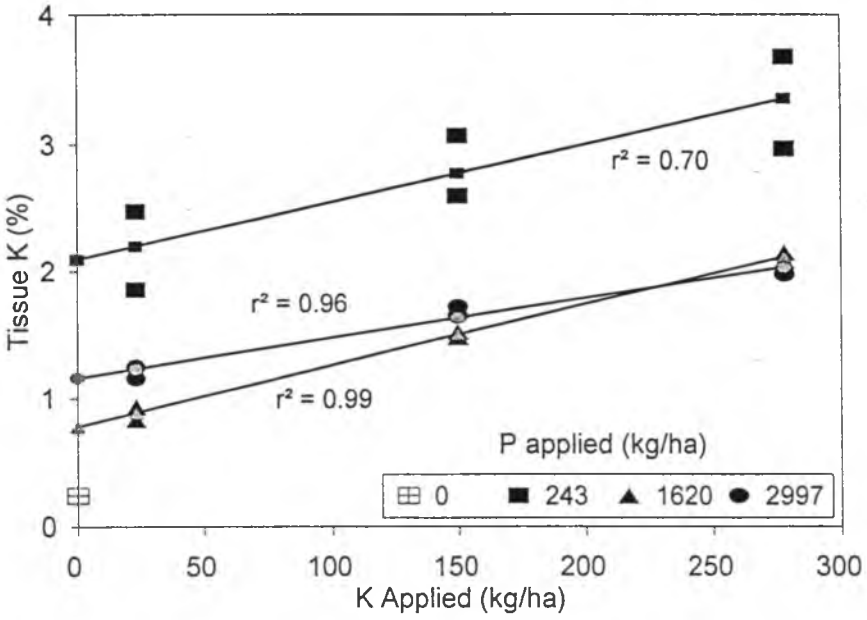

Fig. 26. Effect of K Application on Chinese Cabbage Tissue K Concentration in an Ultisol.

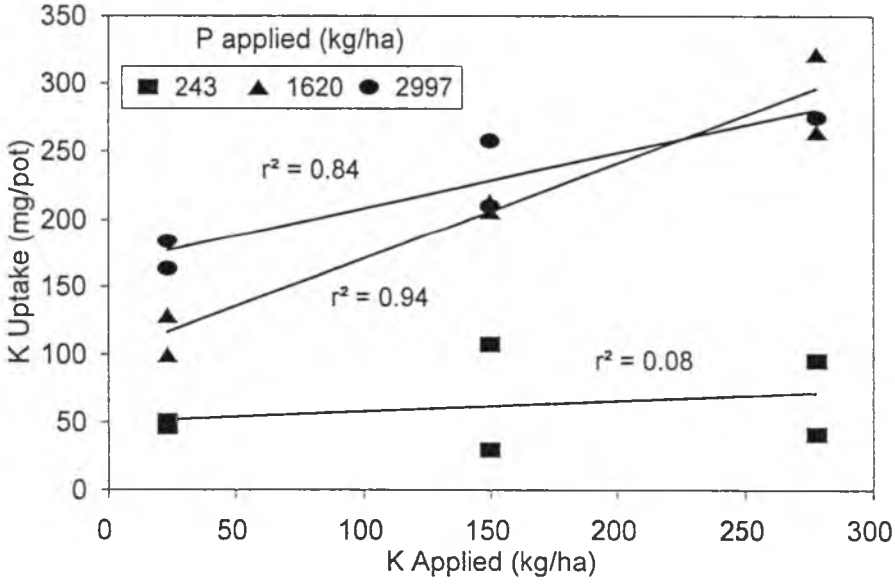

Fig. 27. Effect of K Applications on Chinese Cabbage K Uptake in an Ultisol.

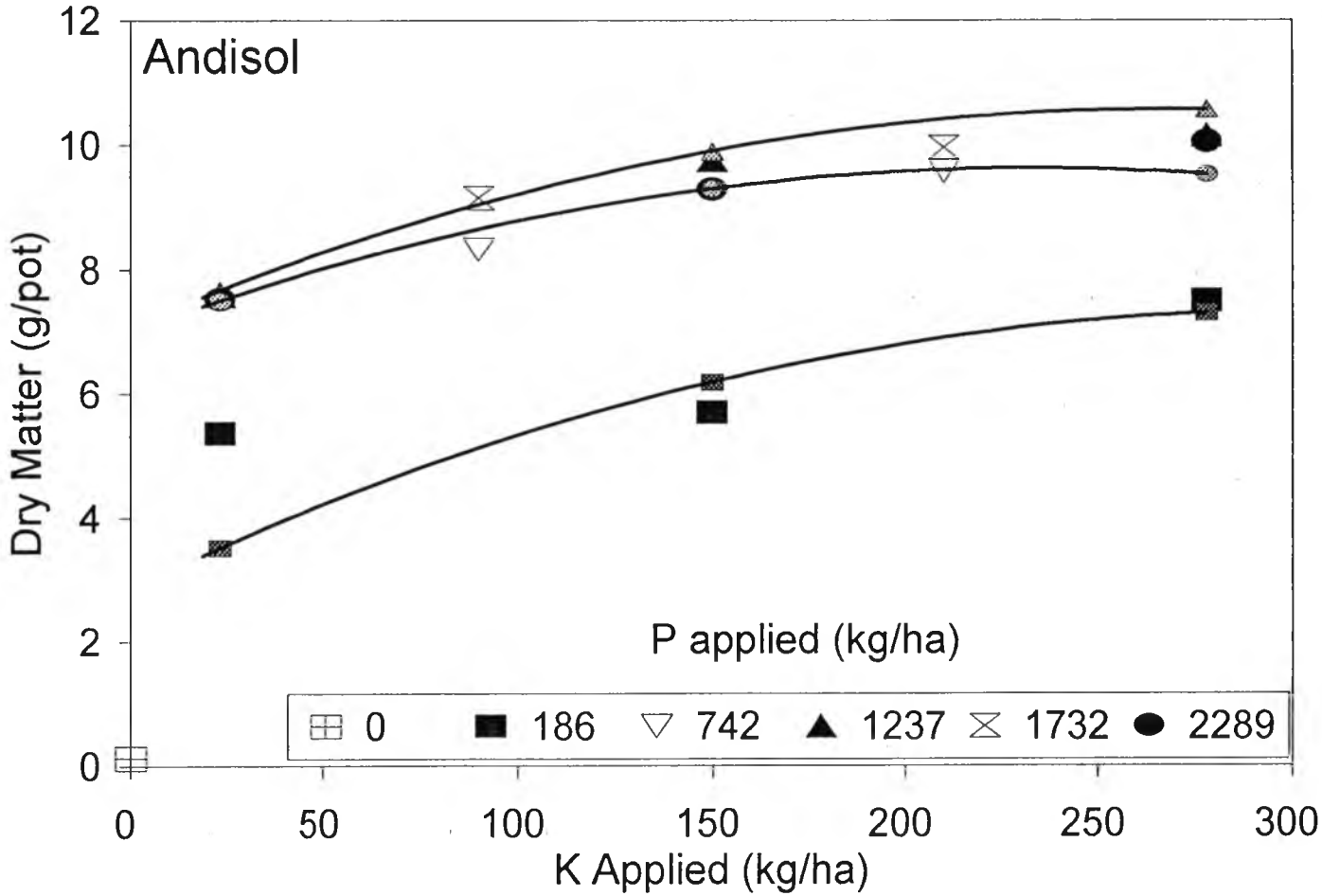

Fig. 28. Response of Chinese Cabbage Dry Matter Yield to K Applications in an Andisol.

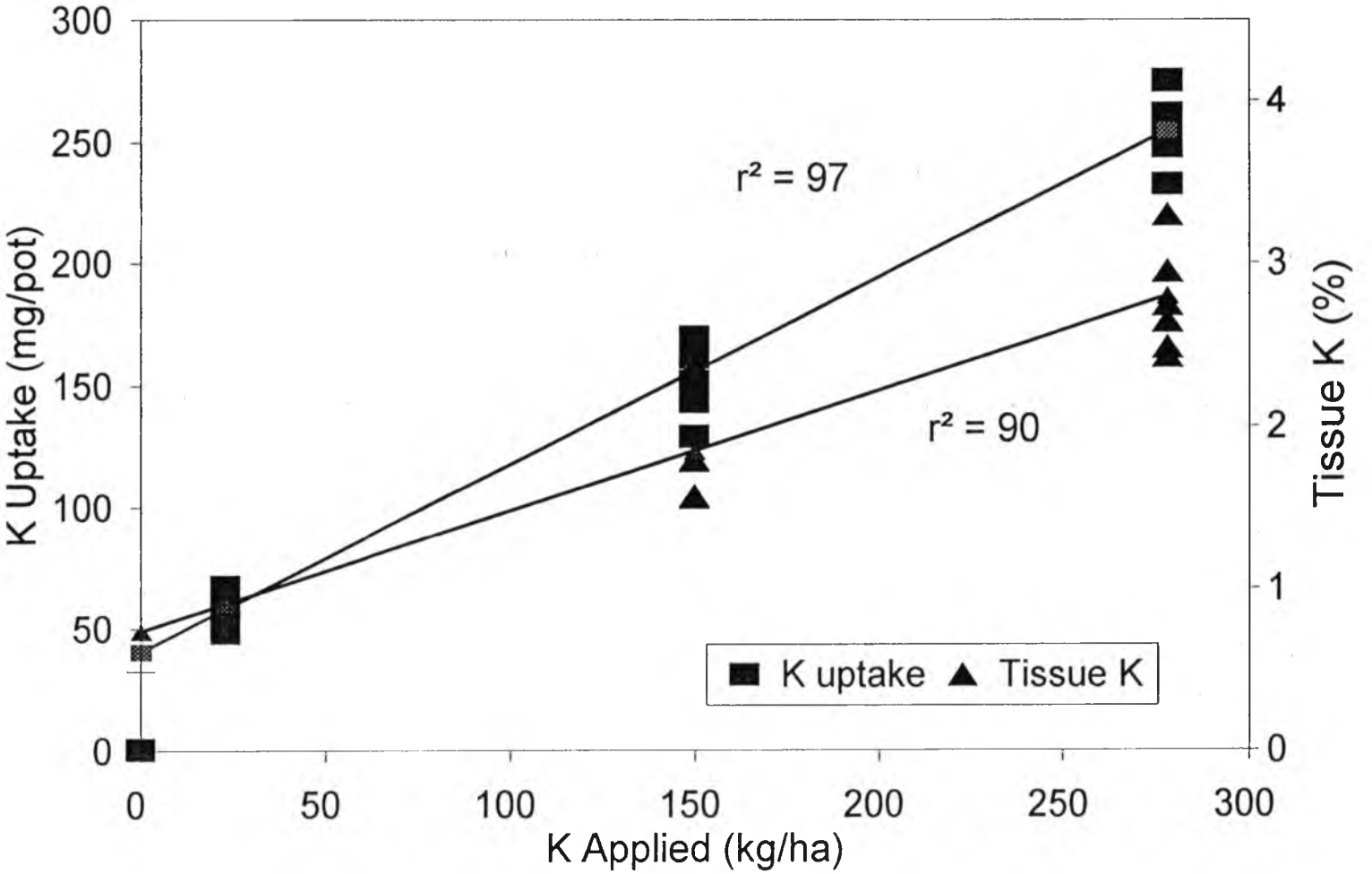

Fig. 29. Effect of K Applications on the K Uptake and Tissue K Concentration of Chinese Cabbage in an Andisol.

Andisol and by the lower temperature during the Andisol trial, which would have decreased both plant root growth and the rate of K diffusion in soil.

Evaluation of P Extraction Methods

RELATIONSHIPS BETWEEN P EXTRACTED AND PLANT PARAMETERS AND BETWEEN P EXTRACTION METHODS IN SWEET CORN TRIALS

The amount of P extracted by the Modified Truog, Mehlich3, Olsen, and Resin methods was curvilinearly related with sweet corn dry matter yield in the Ultisol with R^2 values of 0.96, 0.97, 0.98, and 0.96, respectively (Figs. 30, 31, 32, and 33). The relationships between P extracted by the four methods and dry matter were basically linear in the Andisol with R^2 of 0.89, 0.80, 0.84, and 0.82 for Modified Truog, Mehlich3, Olsen, and Resin, respectively (Figs. 34, 35, 36, and 37). Phosphorus extracted by these methods was also highly related to tissue P and P uptake in both soils (Figs. 38, 39, 40, 41, 42, and 43). The relationship between Resin P and P uptake was somewhat curvilinear in the Ultisol while it was linear in the Andisol (Figs. 40 and 41). The relationships between Resin P and tissue P were curvilinear in both soils (Figs. 40 and 41).

There were highly linear correlations between Modified Truog, Mehlich3, and Olsen P, with r values all greater or equal to 0.95 in both soils (Figs. 44 and 45). The r values for the correlations between Resin P and the other three methods were slightly lower than the r values among these

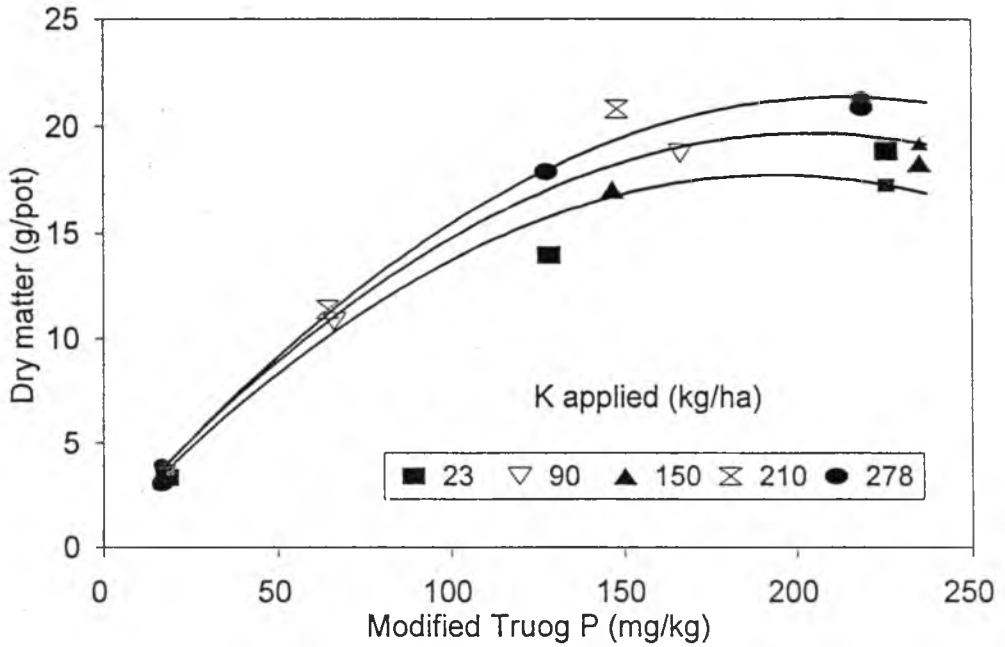

Fig. 30. Response of Sweet Corn Dry Matter Yield to Modified Truog P in an Ultisol.

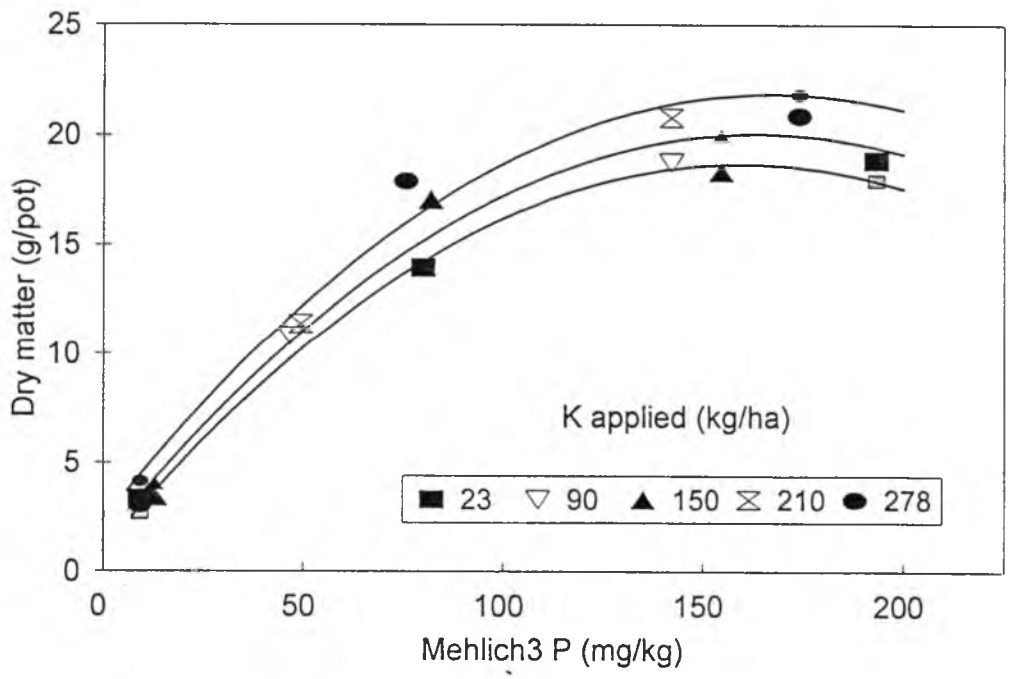

Fig. 31. Response of Sweet Corn Dry Matter Yield to Mehlich3 P in an Ultisol.

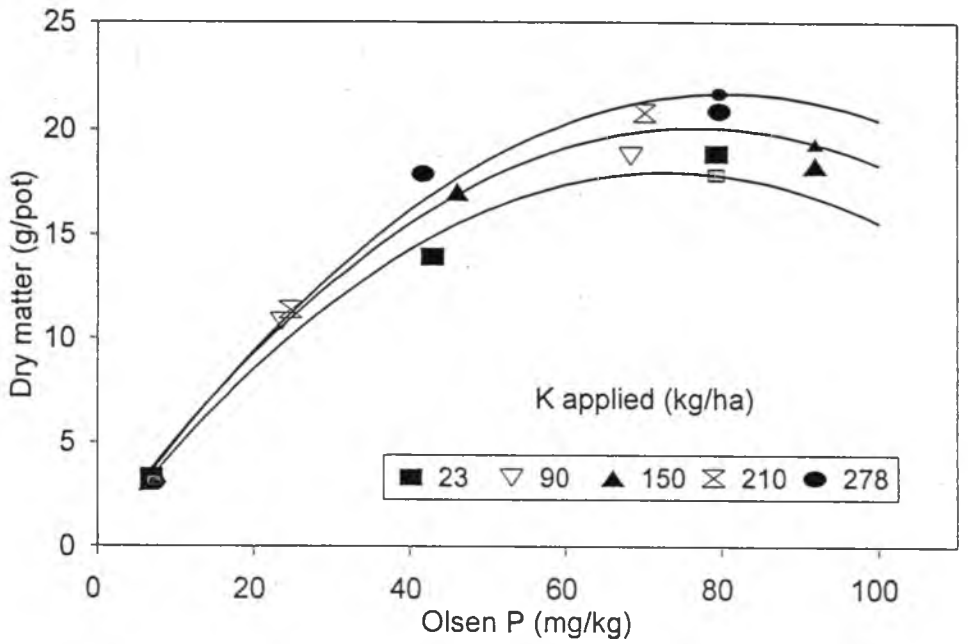

Fig. 32. Response of Sweet Corn Dry Matter Yield to Olsen P in an Ultisol.

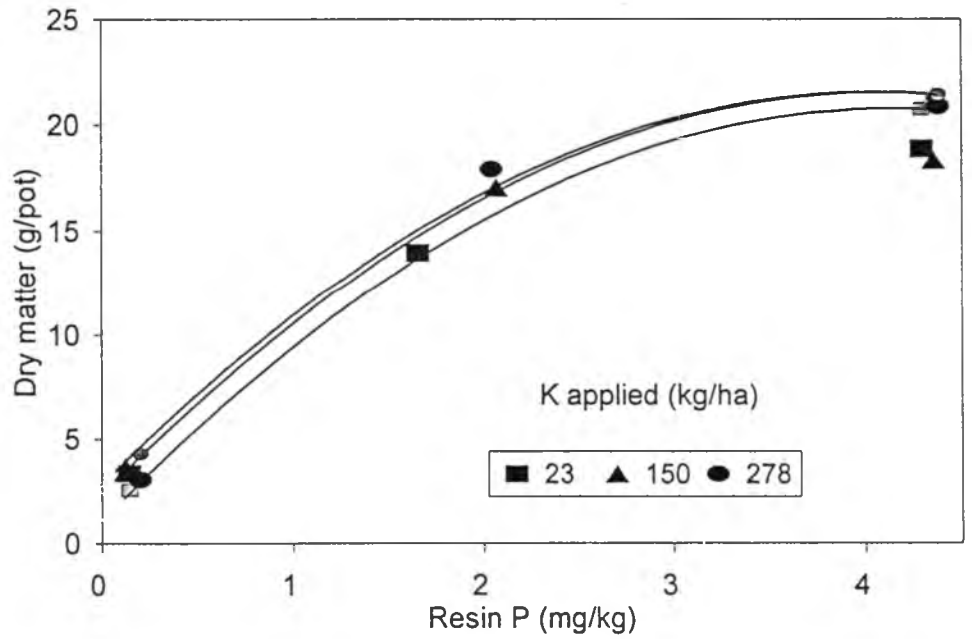

Fig. 33. Response of Sweet Corn Dry Matter Yield to Resin P in an Ultisol.

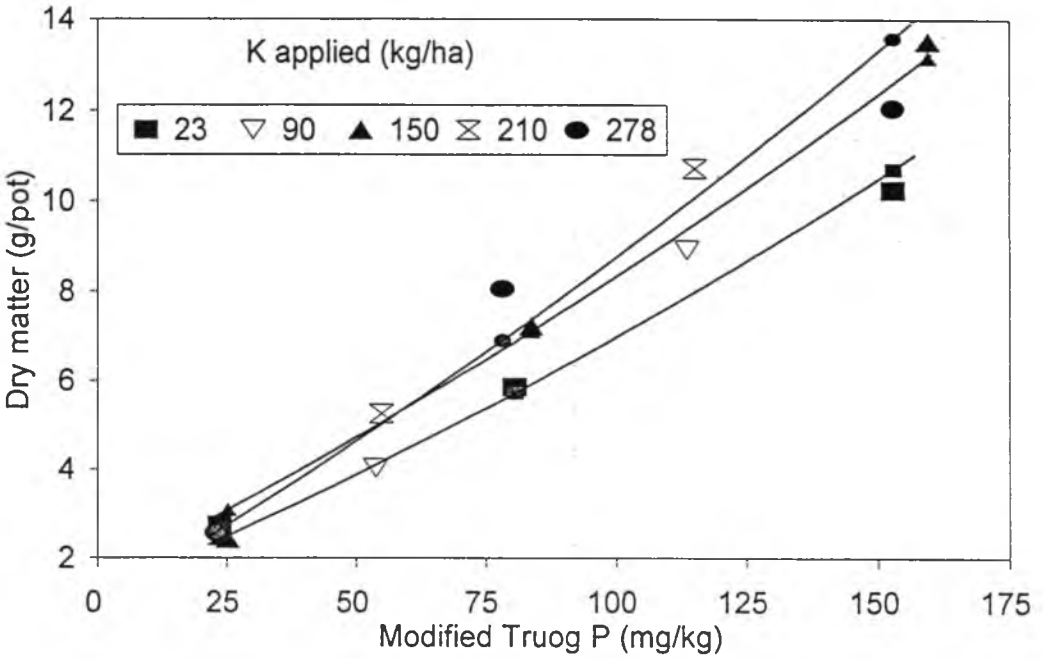

Fig. 34. Response of Sweet Corn Dry Matter Yield to Modified Truog P in the Andisol.

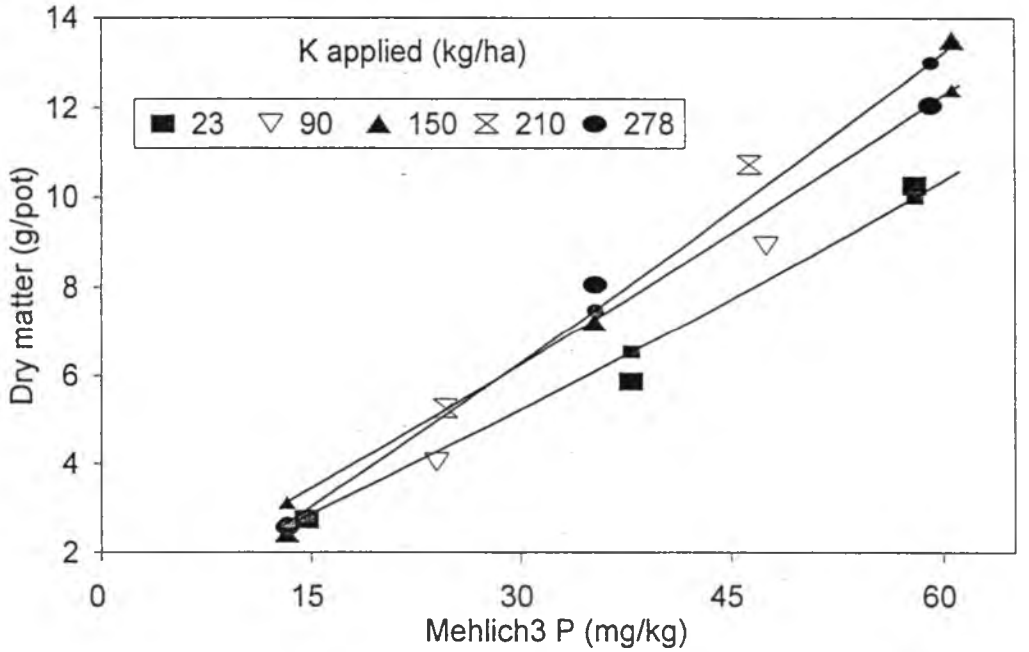

Fig. 35. Response of Sweet Corn Dry Matter Yield to Mehlich3 P in an Andisol.

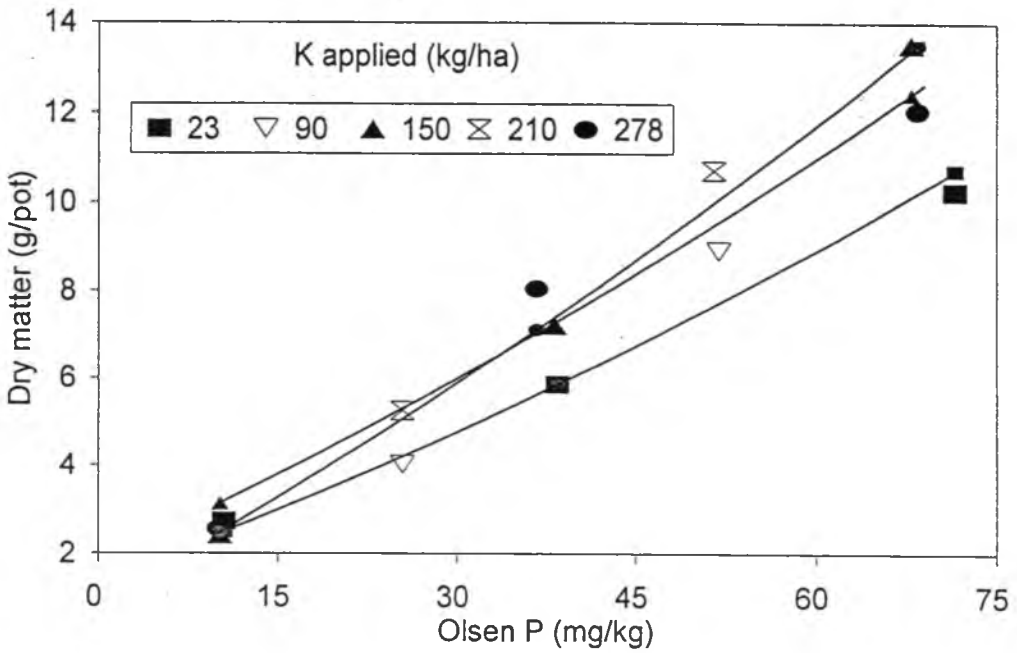

Fig. 36. Reponse of Sweet Corn Dry Matter Yield to Olsen P in an Andisol.

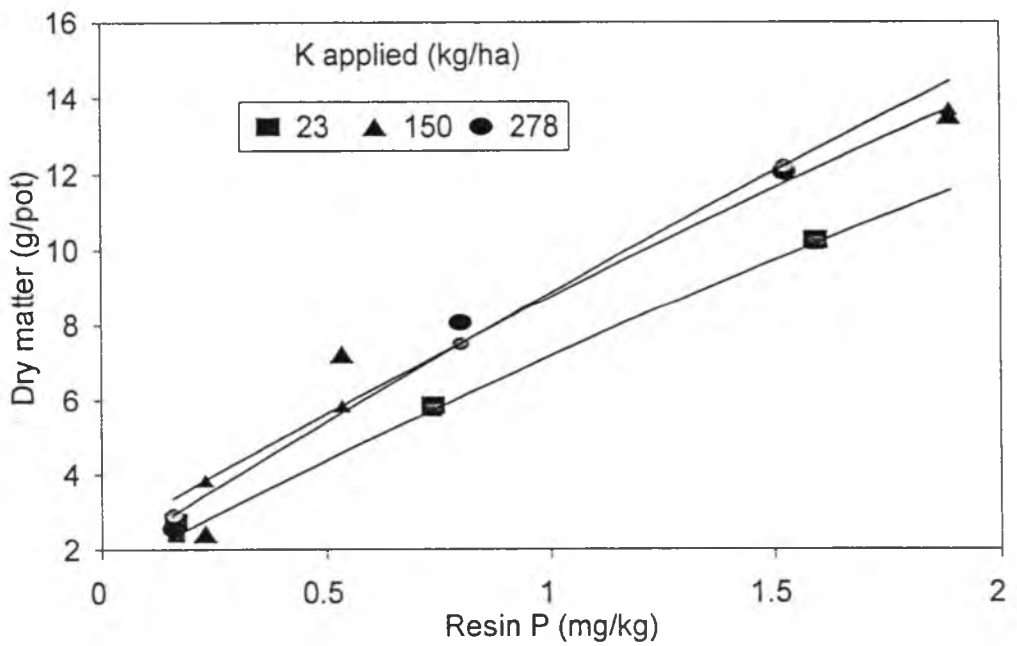

Fig. 37. Reponse of Sweet Corn Dry Matter Yield to Resin P in an Andisol.

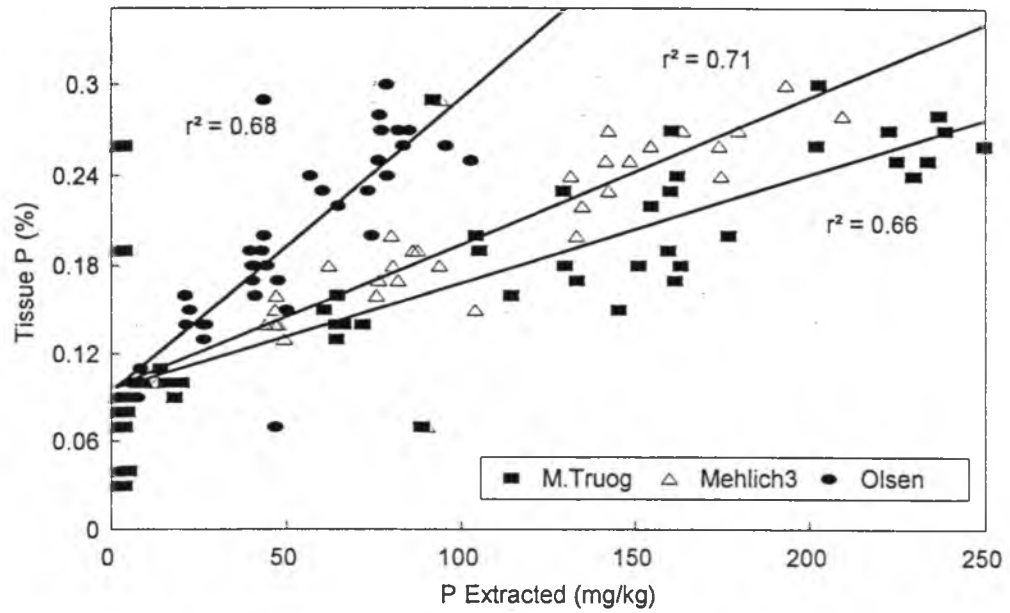

Fig. 38. Relationship between Tissue P Concentration and P Extracted for the Sweet Corn Trial in an Ultisol.

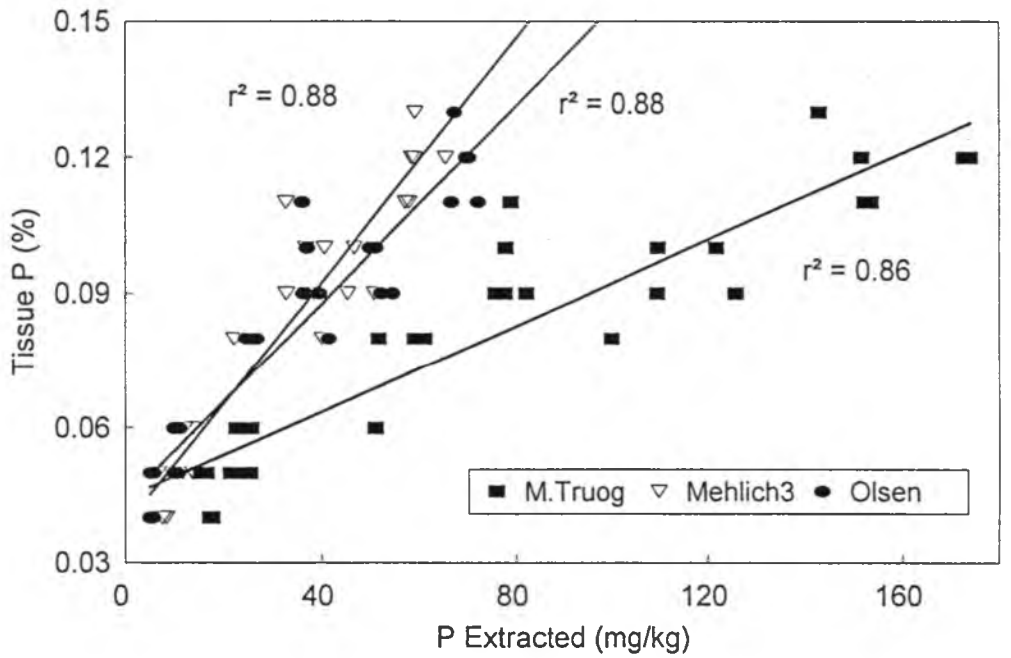

Fig. 39. Relationship between P Extracted and Tissue P Concentration for the Sweet Corn Trial in an Andisol.

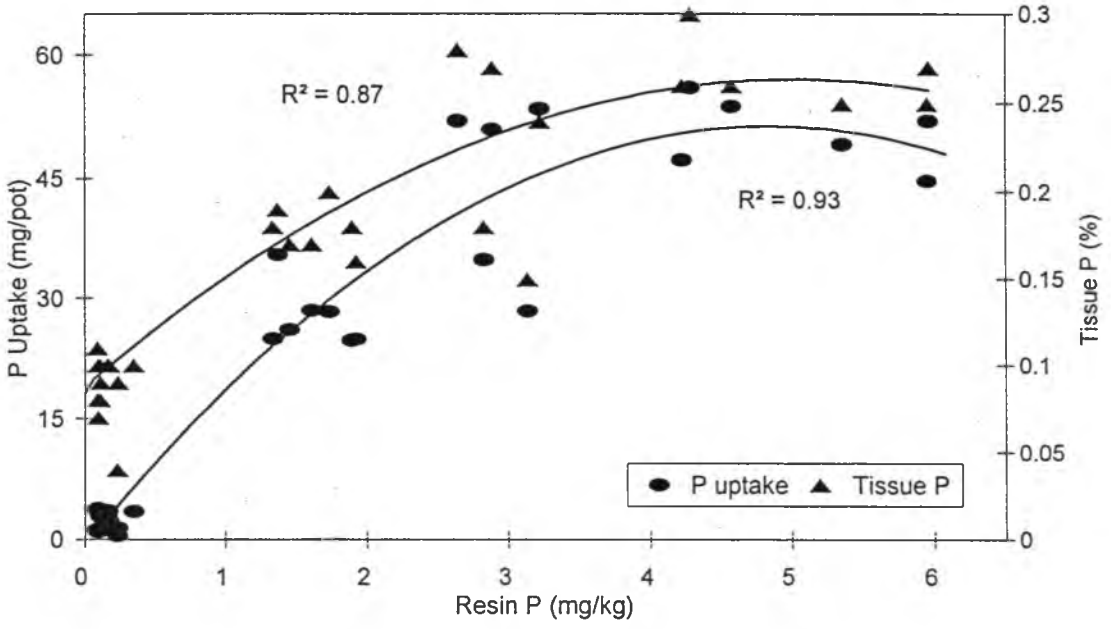

Fig. 40. Relationship of Resin P with P Uptake and Tissue P Concentration for the Sweet Corn Trial in an Ultisol.

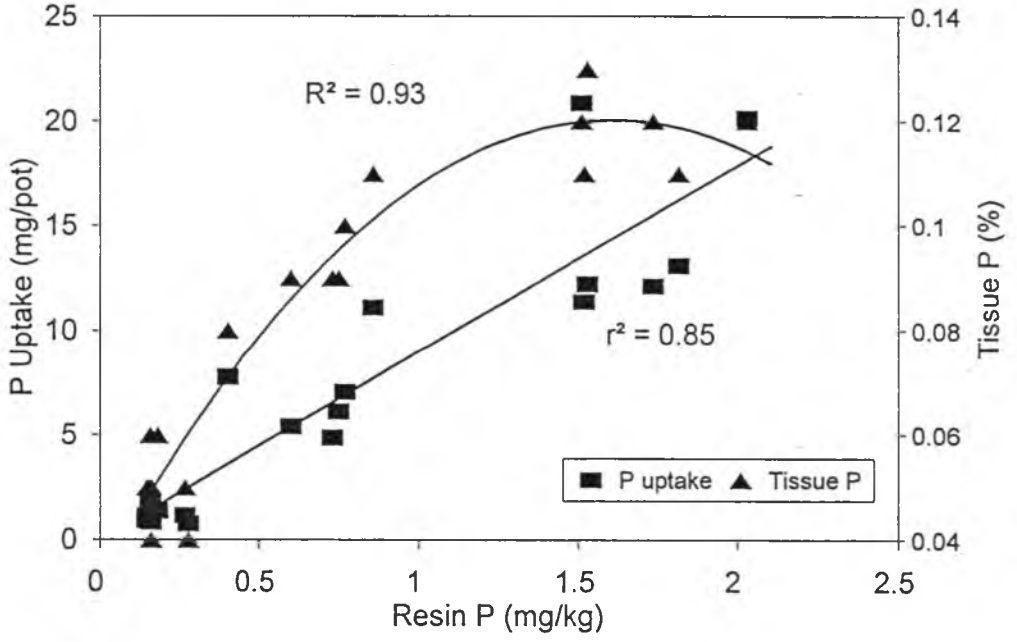

Fig. 41. Relationship of Resin P with P Uptake and Tissue P Concentration for the Sweet Corn Trial in an Andisol.

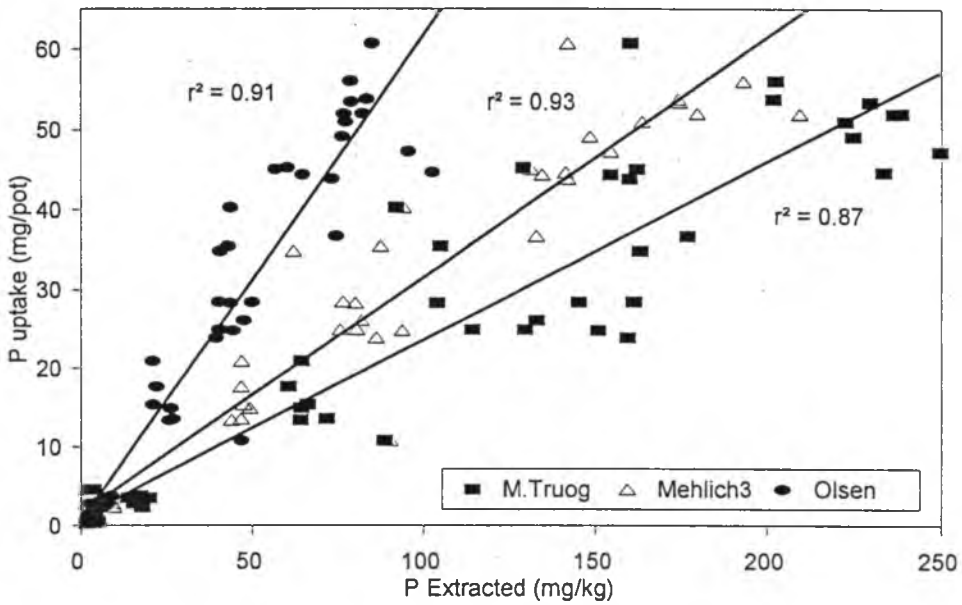

Fig. 42. Relatioship between P Uptake and P Extracted for the Sweet Corn Trial in an Ultisol.

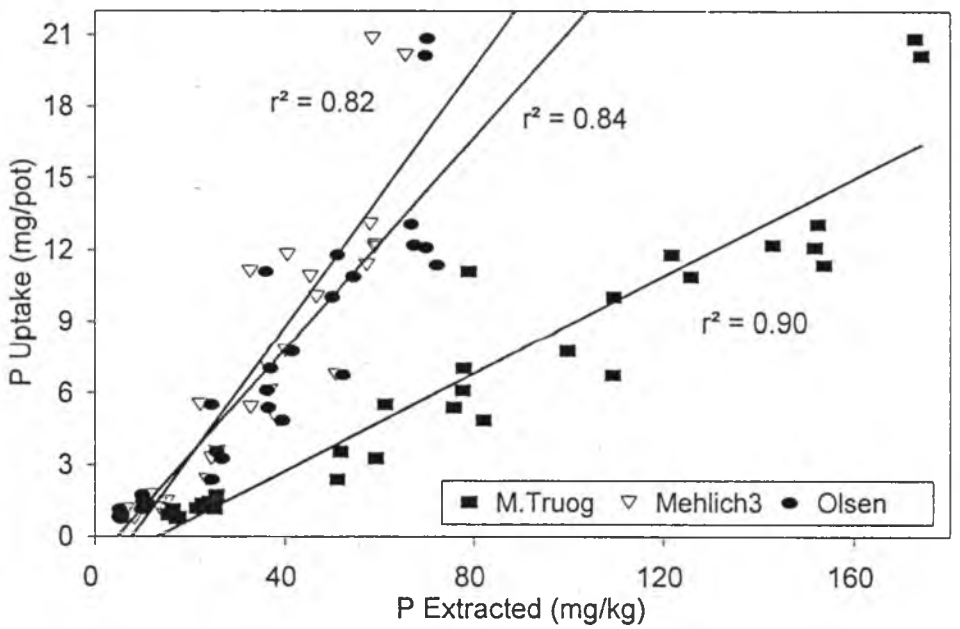

Fig. 43. Relationship between P Uptake and P Extracted for the Sweet Corn Trial in an Andisol.

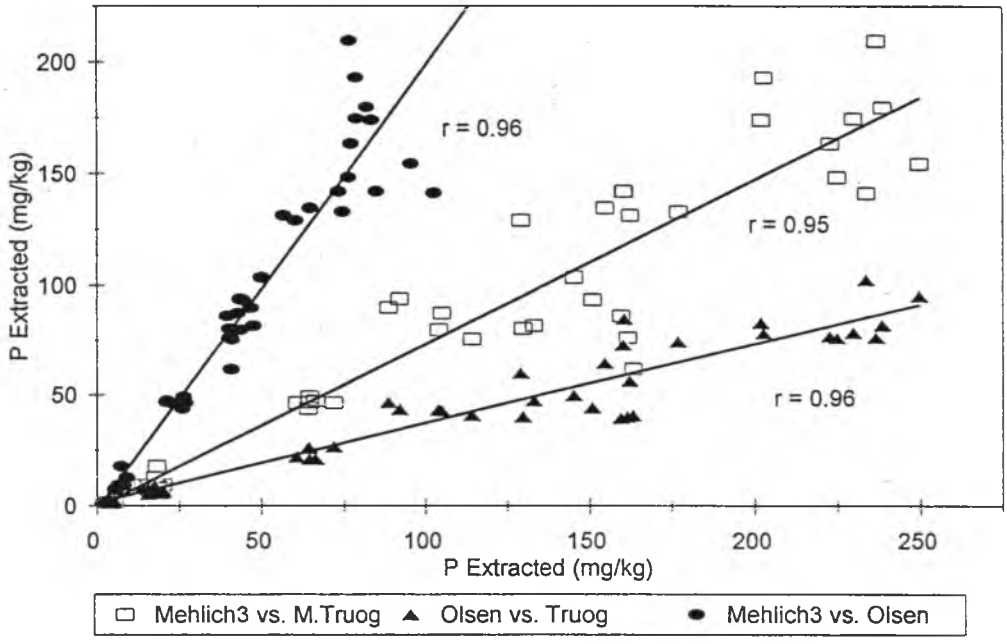

Fig. 44. Correlations between P Extraction Methods for the Sweet Corn Trial in an Ultisol.

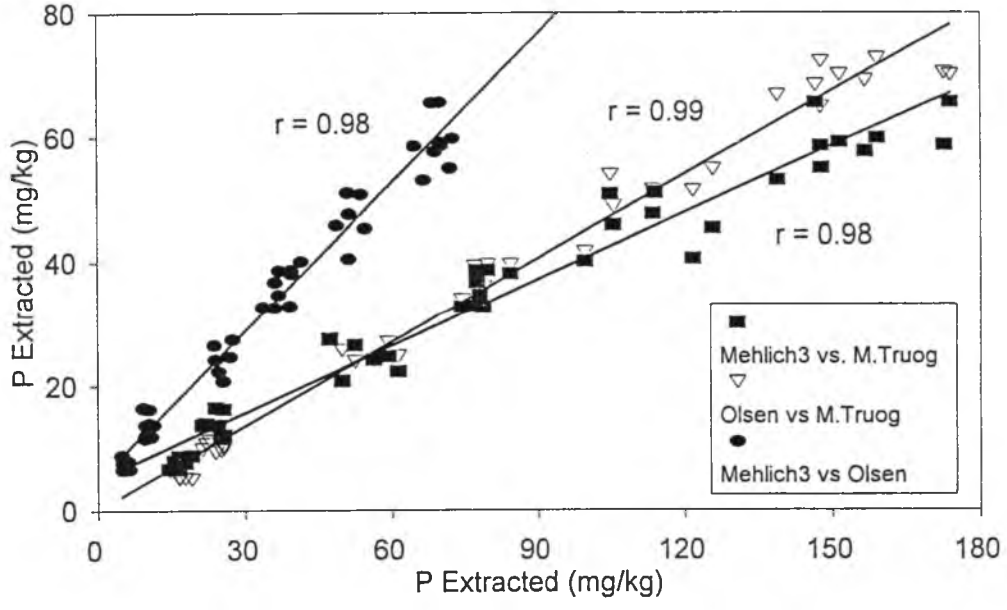

Fig. 45. Correlations between P Extraction Methods for the Sweet Corn Trial in an Andisol.

three methods, especially in the Ultisol. However, the r values for Resin versus the other three methods were all greater or equal to 0.89 (Figs. 46 and 47). Correlations between the methods were higher in the Andisol than in the Ultisol. This might be due to the fact that Andisol samples were kept moist while Ultisol samples were air dried. Extraction methods for P may have results with lower variation on moist soil samples than on air-dried soil samples (Jackson, 1958).

RELATIONSHIPS BETWEEN P EXTRACTED AND PLANT PARAMETERS AND BETWEEN P EXTRACTION METHODS IN CHINESE CABBAGE TRIALS

The relationships between Chinese cabbage dry matter yield and P extracted by Modified Truog and Mehlich3 were very similar to the relationships between dry matter yield and P applied in both soils (Figs. 48-51). Both tissue P and P uptake were curvilinearly related to Modified Truog P and Mehlich3 P in both soils with R^2 values greater than or equal to 0.89 (Figs. 52-55). Mehlich3 P was highly correlated with Modified Truog P with r values of 0.99 and 0.98 for the Ultisol and Andisol, respectively (Fig. 56). The regression equations for the relationships between these two methods are given in Appendix G.

COMPARISONS OF THE ACCURACY OF DIAGNOSES, THE SENSITIVITY OF P TEST VALUES, AND C.V. FOR SAMPLING FOR P EXTRACTION METHODS

Accuracy of the diagnoses: Accuracy of diagnoses was assessed in the sweet corn trial on the Ultisol and in both

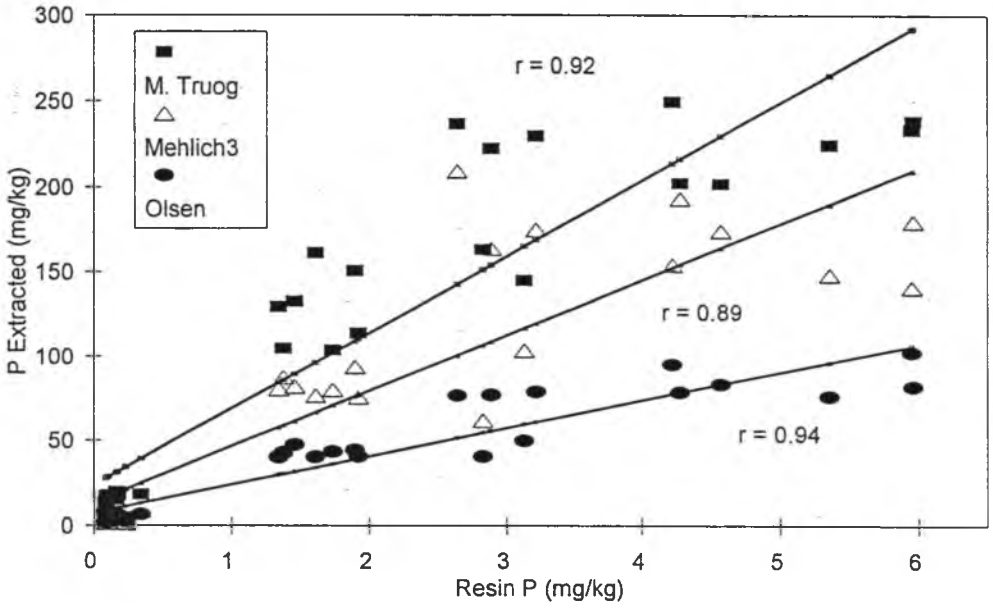

Fig. 46. Correlations between Resin and Other Extraction Methods for the Sweet Corn Trial in an Ultisol.

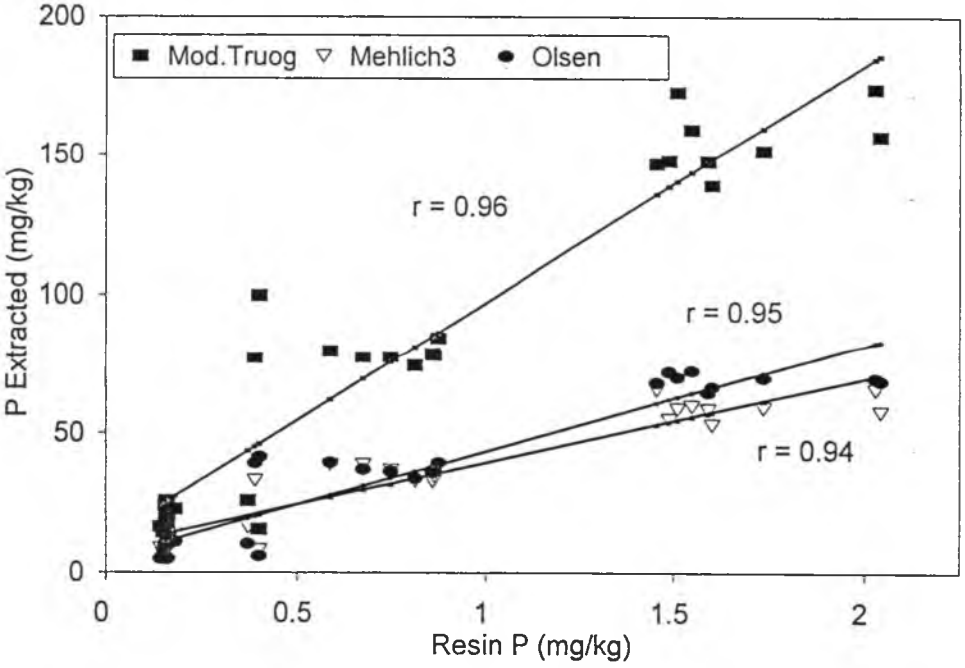

Fig. 47. Correlations between Resin and the Other Extraction Methods for the Sweet Corn Trial in an Andisol.

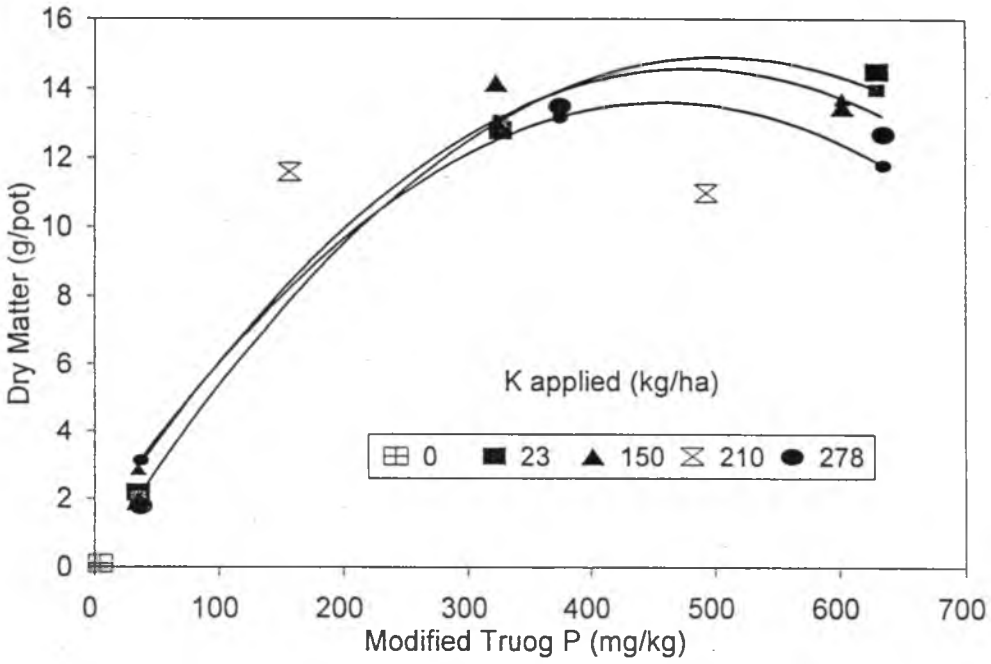

Fig. 48. Response of Chinese Cabbage Dry Matter Yield to Modified Truog P in an Ultisol.

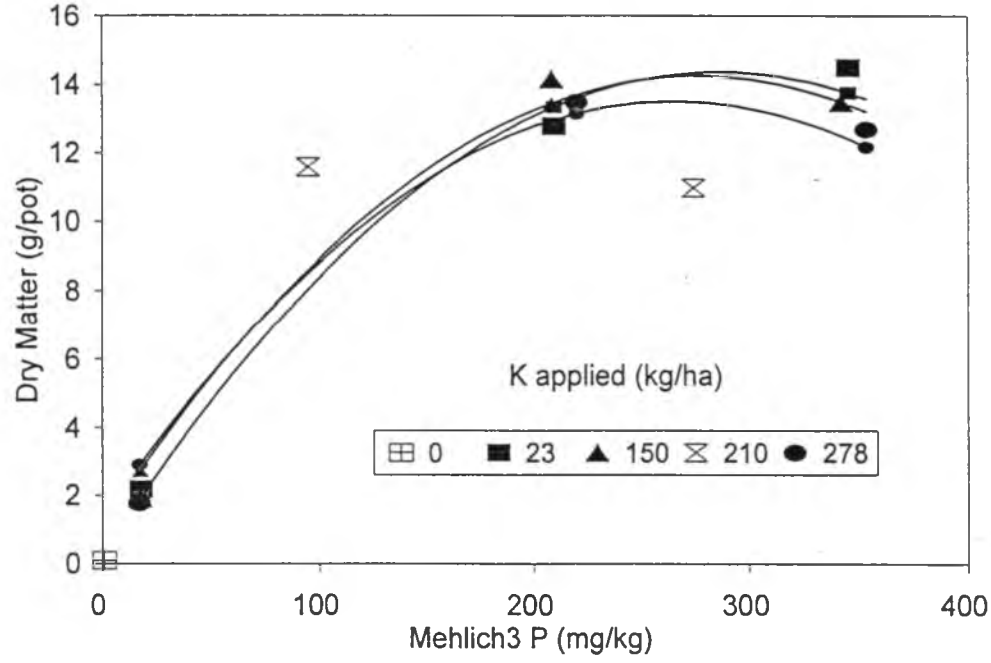

Fig. 49. Response of Chinese Cabbage Dry Matter Yield to Mehlich3 P in an Ultisol.

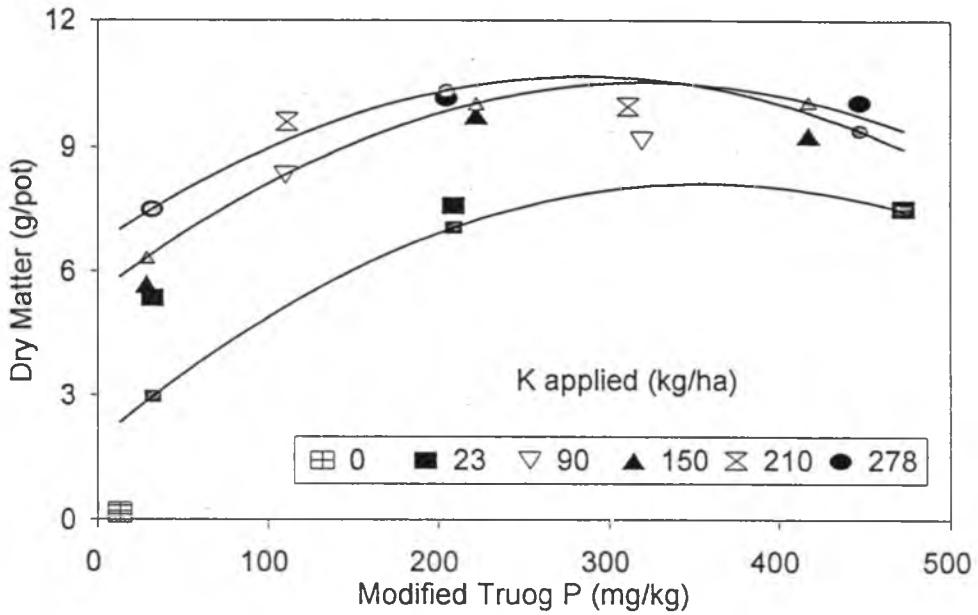

Fig. 50. Response of Chinese Cabbage Dry Matter Yield to Modified Truog P in an Andisol.

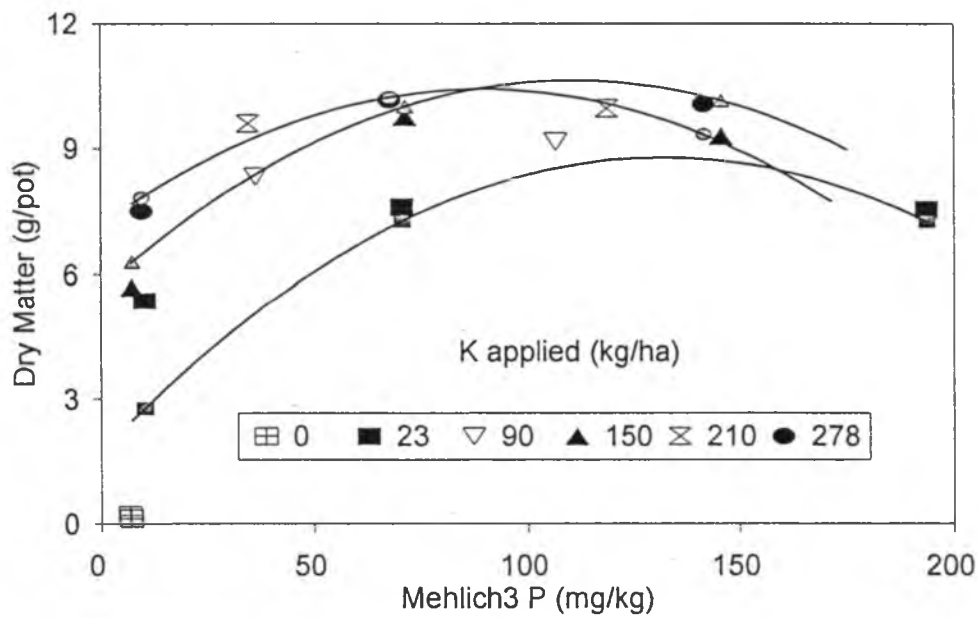

Fig. 51. Response of Chinese Cabbage Dry Matter Yield to Mehlich3 P in an Andisol.

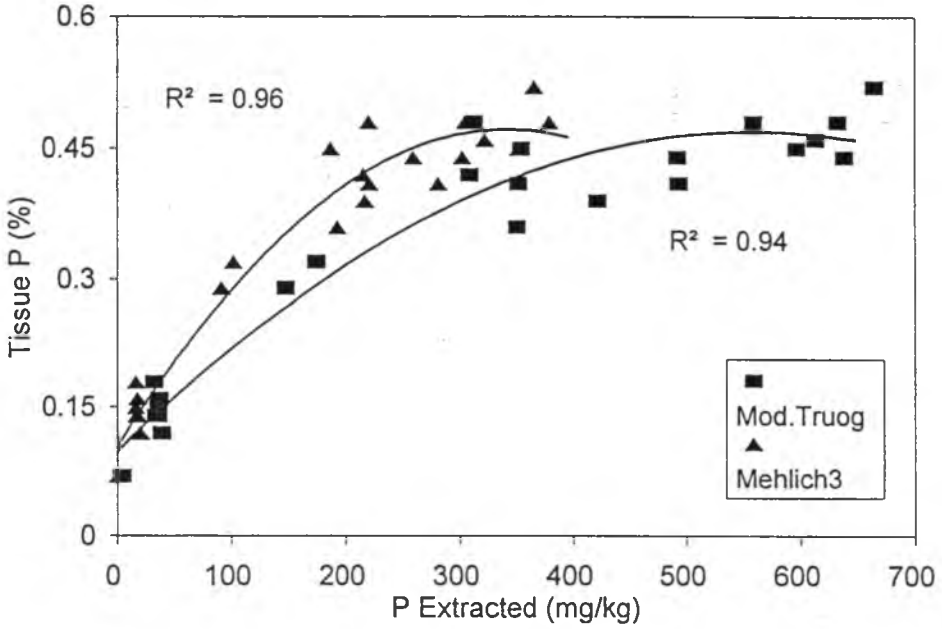

Fig. 52. Relationship between P Extracted and Chinese CabbageTissue P Concentration in an Ultisol.

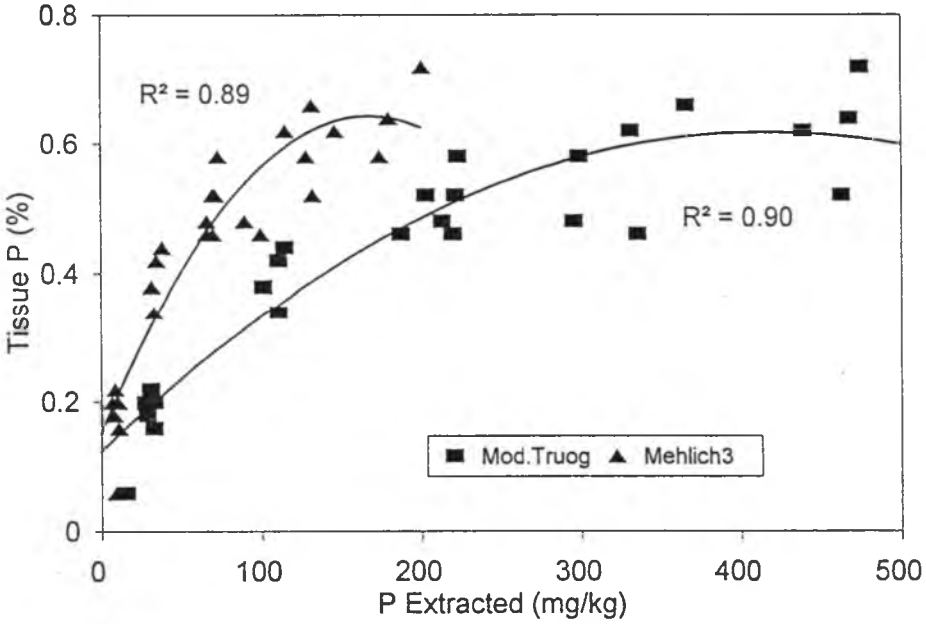

Fig. 53. Relationship between P Extracted and Chinese Cabbage Tissue P Concentration in an Andisol.

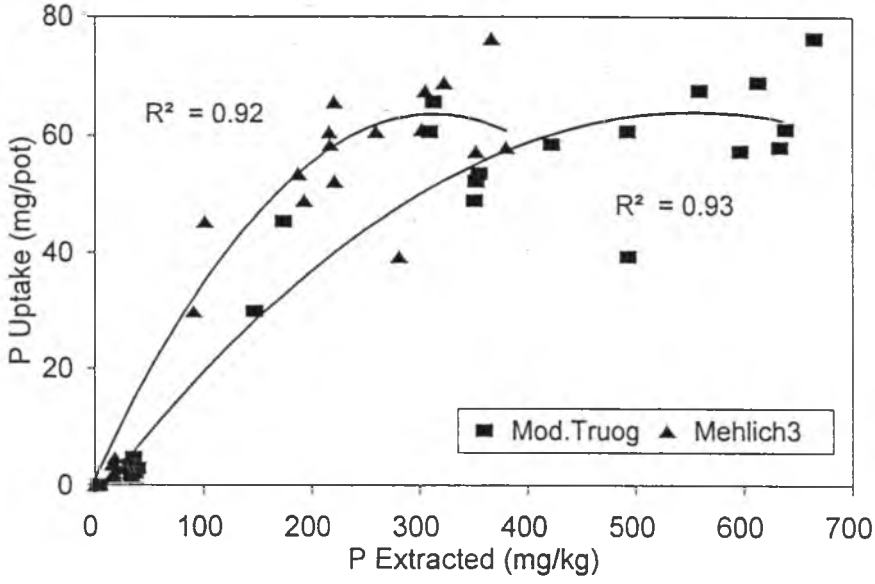

Fig. 54. Relationship between P Extracted and Chinese Cabbage P Uptake in an Ultisol.

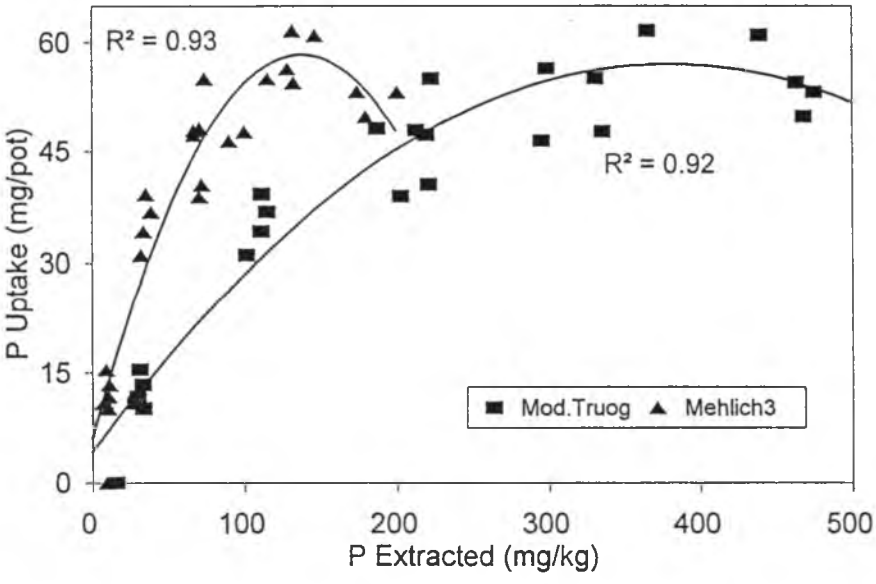

Fig. 55. Relationship between P Extracted and Chinese Cabbage P Uptake in an Andisol.

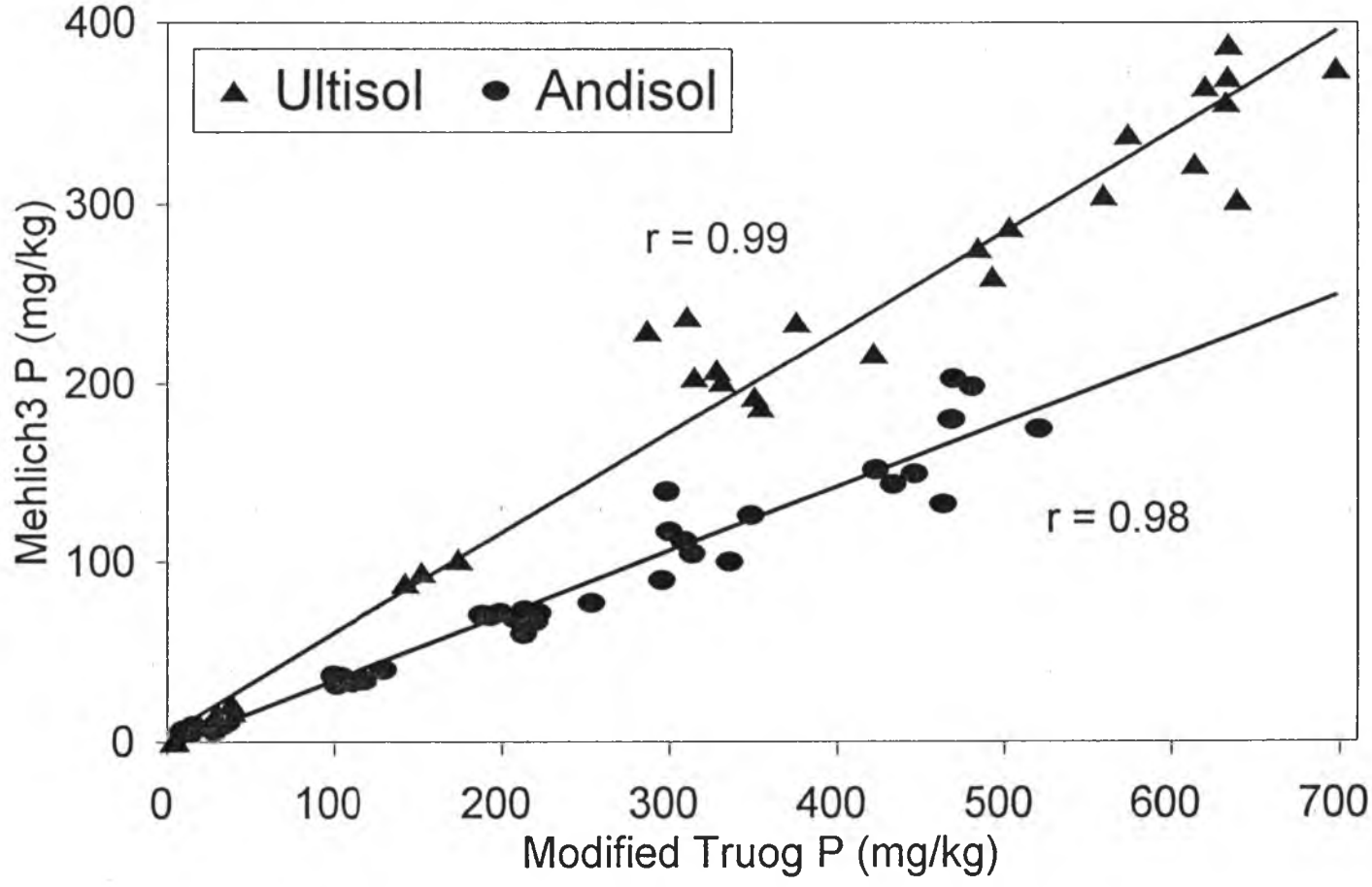

Fig. 56. Correlations between Modified Truog P and Mehlich3 P for Chinese Cabbage Trial in Two Soils.

Chinese cabbage trials using the critical level and maximum yield estimates from the fitted linear plateau model. Results from the sweet corn trial on the Andisol were not used in this assessment because we were unable to obtain estimates for the maximum yield or critical soil P level from this trial. For sweet corn in the Ultisol, Olsen P gave the highest percentage of correct diagnoses (90.48%) and the lowest percentage of P test values within the critical range, and Mehlich3 P ranked second (Table 10 and Figs. 57-60). No assessment of the accuracy of diagnoses could be made where P test values were within the critical range (95% confidence interval of critical P level) because these values are not significantly above or below the critical P level. Therefore, more P test values falling in the interval indicate low precision of the diagnoses. Modified Truog P and Resin P gave similar percentages of correct diagnoses and percentages of P test values within the critical range. In terms of incorrect diagnoses, all four methods performed similarly (Table 10 and Figs. 57-60). For the Chinese cabbage trial in the Ultisol, the accuracy of diagnoses from Mehlich3 P was the same as that from Modified Truog P (Table 10 and Figs. 61 and 62). However, for the Chinese cabbage trial in the Andisol, Mehlich3 P had slightly more incorrect diagnoses and more P test values within the critical range than Modified Truog (Table 10 and Figs. 63 and 64).

Table 10. Comparisons of the Accuracy of Diagnoses for Four Soil P Extraction Methods.

	Predictions						% of critical range§
	Incorrect		Interval		Correct		
	No.†	%	No.‡	%	No.¶	%	
	Sweet corn in the Ultisol						
Mod.Truog	3/42#	7.14	3/42	7.14	36/42	85.71	11.60
Mehlich3	3/42	7.14	2/42	4.76	37/42	88.10	9.71
Olsen	3/42	7.14	1/42	2.38	38/42	90.48	9.71
Resin	2/27	7.41	2/27	7.41	23/27	85.19	11.02
	Chinese cabbage in the Ultisol						
Mod.Truog	7/33	21.21	3/33	9.09	23/33	69.70	11.70
Mehlich3	7/33	21.21	3/33	9.09	23/33	69.70	9.06
	Chinese cabbage in the Andisol						
Mod.Truog	7/39	17.95	3/39	7.69	29/39	74.36	13.05
Mehlich3	8/39	20.51	4/39	10.26	27/39	69.23	12.50

† The observations falling in the area where dry matter yields were significantly below the yield plateau and P test values were above the critical range and where dry matter yields were not significantly below the yield plateau and P test values were below the critical range.

‡ The observations falling in critical P range.

¶ The observations falling in the area where dry matter yields were significantly below the yield plateau and P test values were below the critical range and where dry matter yields were not significantly below the yield plateau and P test values were above the critical range.

§ Ratio (expressed as percentage) of estimated critical range to the range of soil P test values between the upper and lower 10th percentile.

Denominator is the number of total observations in each crop and soil combination.

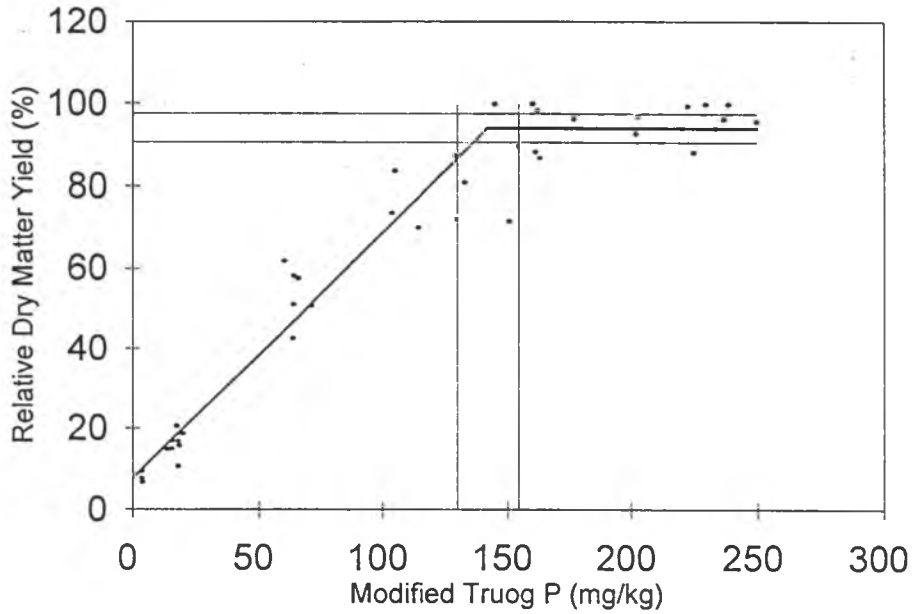

Fig. 57. Determination of Critical Modified Truog P Range and Accuracy of Diagnoses for Young Sweet Corn in an Ultisol Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Relative Yield Estimates

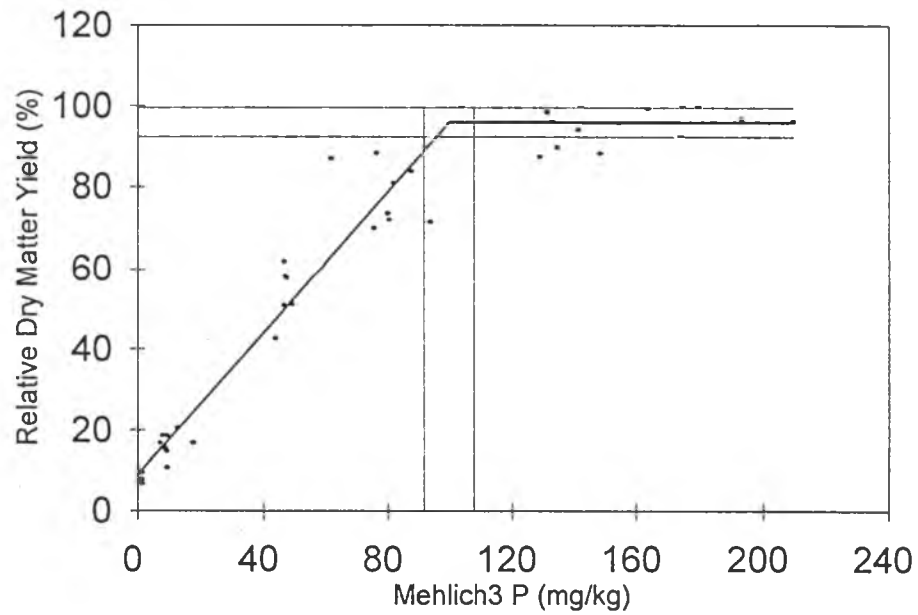

Fig. 58. Determination of Critical Mehlich3 P Range and Accuracy of Diagnoses for Young Sweet Corn in an Ultisol Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Relative Estimates.

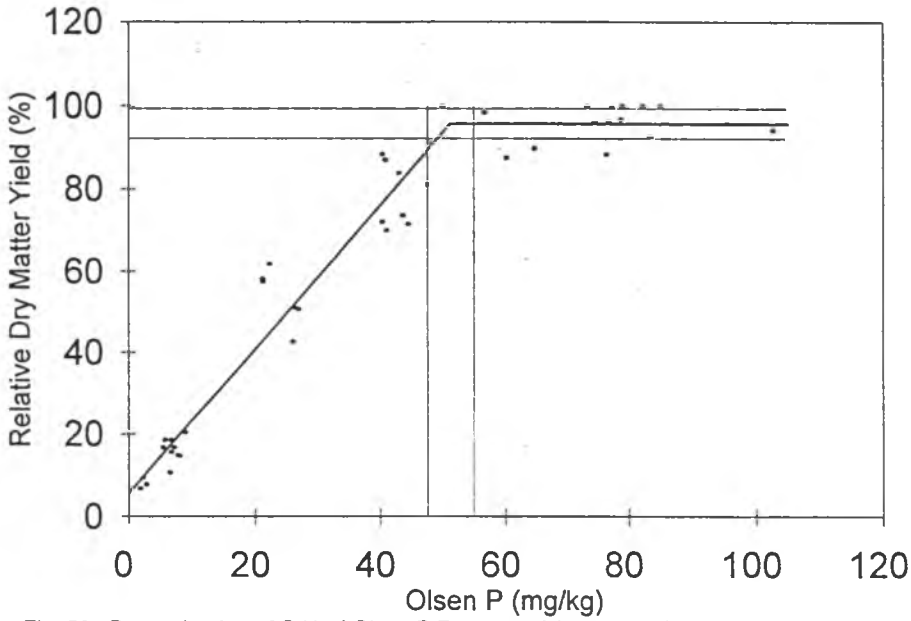

Fig. 59. Determination of Critical Olsen P Range and Accuracy of Diagnoses for Young Sweet Corn in an Ultisol Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Yield Estimates.

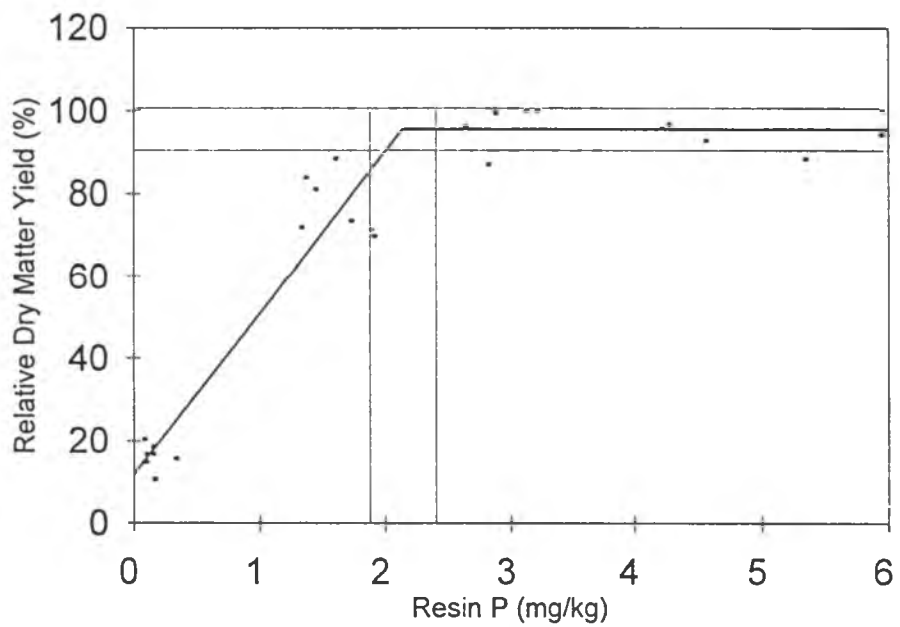

Fig. 60. Determination of Critical Resin P Range and Accuracy of Diagnoses for Young Sweet Corn in an Ultisol Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Yield Estimates.

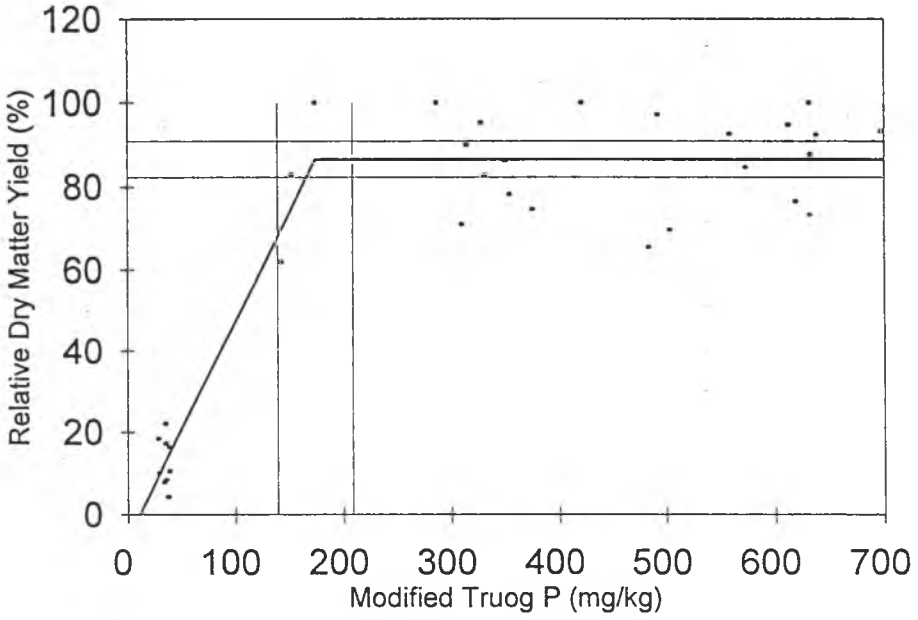

Fig. 61. Determination of Critical Modified Truog P Range and Accuracy of Diagnoses for Young Chinese Cabbage in an Ultisoll Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Relative Yield Estimates.

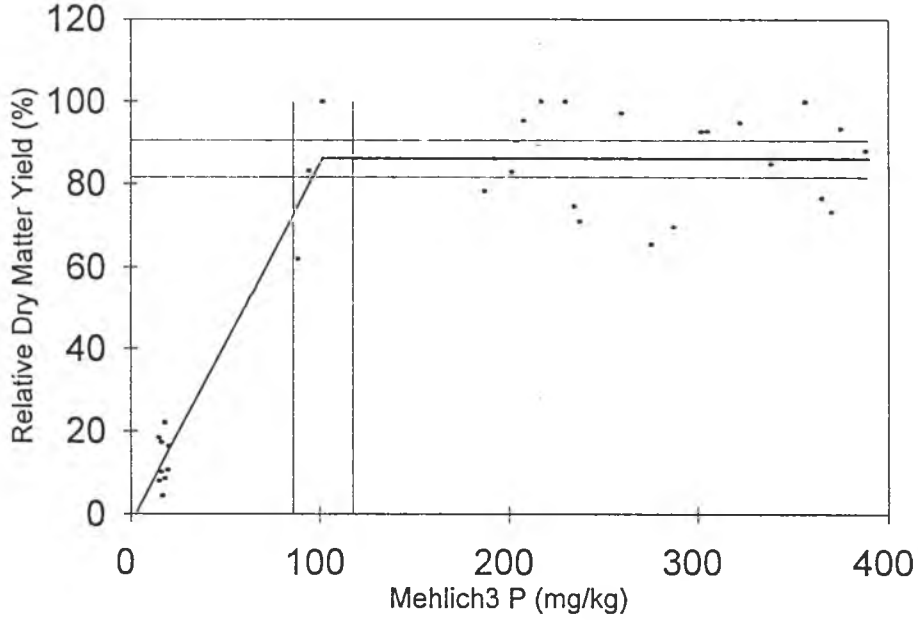

Fig. 62. Determination of Critical Mehlich3 P Range and Accuracy of Diagnoses for Young Chinese Cabbage in an Ultisoll Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Relative Yield Estimates.

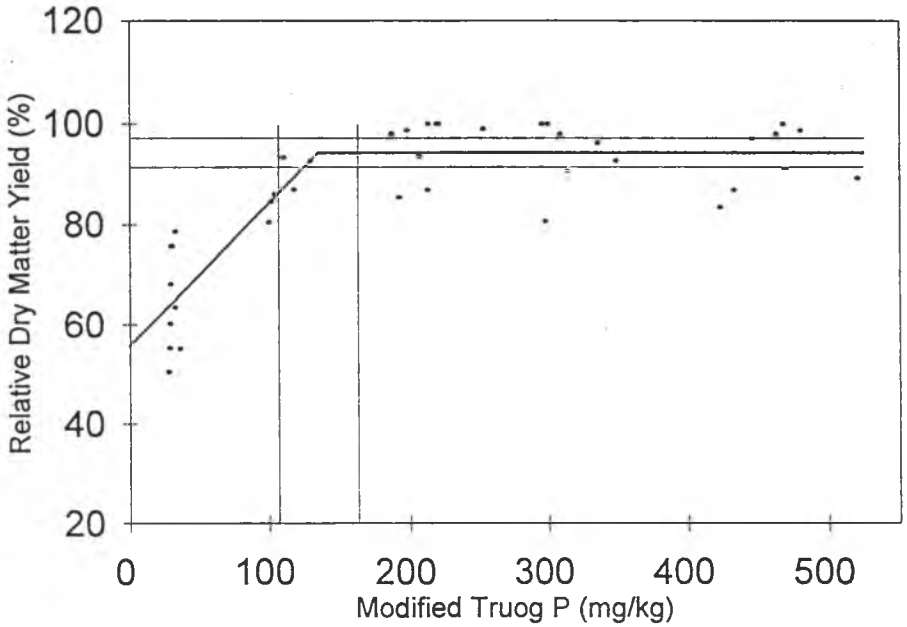

Fig. 63. Determination of Critical Modified Truog P Range and Accuracy of Diagnoses for Young Chinese Cabbage in an Andisol Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Relative Yield Estimates.

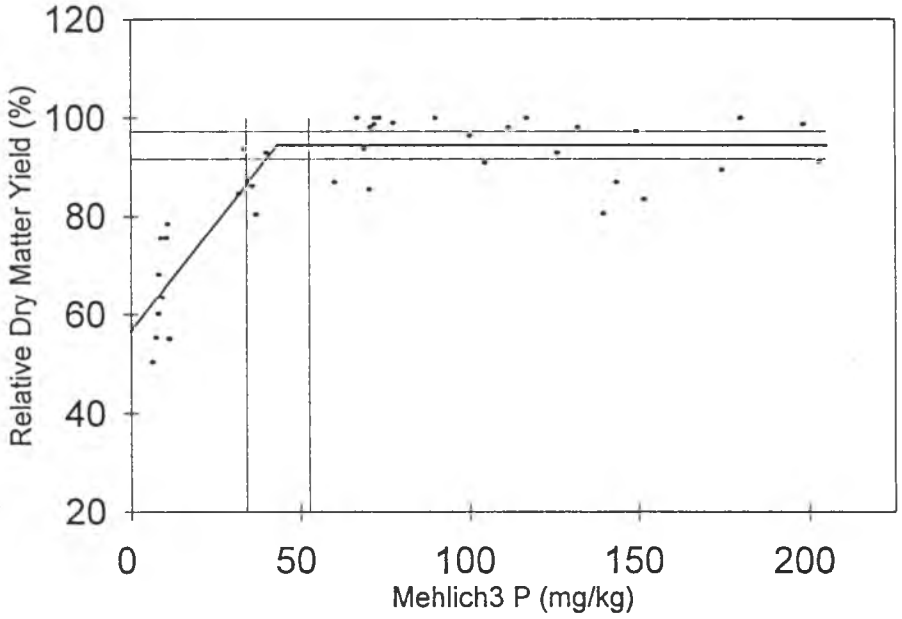

Fig. 64. Determination of Critical Mehlich3 P Range and Accuracy of Diagnoses for Young Chinese Cabbage in an Andisol Using a Linear Plateau Model. Dotted Lines Indicate 95% Confidence Intervals for Critical P Level and Maxmum Relative Yield Estimates.

The ratio (expressed as a percentage) between its critical range (or 95% confidence interval for an estimated critical level) and the range of soil P test values between the upper and lower 10th percentile was used as a measure of the precision of diagnosis. A high value for this ratio means there is a wide range of soil P levels for which diagnosis is uncertain and therefore indicates low precision for the method. For the sweet corn trial in the Ultisol, Olsen P and Mehlich3 P were the most precise in terms of this ratio. Based on this criterion, Resin P ranked second and Modified Truog P ranked last (Table 10). For the two Chinese cabbage trials, Mehlich3 P was more precise than Modified Truog in both soils (Table 10).

The sensitivity of each method's P test values to soil P levels: In cases where several methods are all well correlated with plant performance, the sensitivity of their respective test values to changes in soil P levels provides an additional selection criterion. This sensitivity was measured using two coefficients, which will be referred to as sensitivity coefficients A and B. Sensitivity coefficient A is calculated as the reciprocal of the estimated slope in the linear plateau model that was used for estimating the extractable P critical level. A high value for coefficient A indicates a greater change in the soil P test value per unit increase in plant dry matter. Sensitivity coefficient B is the ratio of P extracted to P applied (which is the

slope in the fitted linear regression models). Higher value for the coefficient B indicates greater sensitivity of the extractant to P added. A very low value for either of these coefficients is undesirable because high precision will be required in using the method for soil analysis. More generally, a lower value for either coefficient indicates that the critical levels must be estimated with greater precision to obtain accurate diagnoses or recommendations. Methods with values for coefficient A that are more constant across a range of soils and crops would also make transfer of calibration results more reliable.

For the sweet corn trials, all four of the P extraction methods were compared. In the Ultisol, the methods were ranked from most to least sensitive by both coefficient A and B as follows: Modified Truog P > Mehlich3 P > Olsen P > Resin P. The ranking from the trial on the Andisol was Modified Truog P > Olsen P > Mehlich3 P > Resin P (Table 11 and Figs. 65-68). For the Chinese cabbage trials, Modified Truog P was more sensitive than Mehlich3 in both soils. These results did not depend on which sensitivity coefficient was used (Table 11).

It is interesting to note that sensitivity coefficient A for Mehlich3 was more consistent across the soil-crop combinations tested than it was for the other methods while sensitivity coefficient B was more soil dependent for Mehlich3 than for either Modified Truog or Olsen (Table 11).

Table 11. Sensitivity Coefficient and Coefficient of Variation (%) for Sampling of P Extraction Methods.

Coefficients	P extraction methods			
	Mod. Truog	Mehlich3	Olsen	Resin
	Sweet corn in the Ultisol			
Sensitivity Coef. A†	1.646	1.145	0.570	0.026
Sensitivity Coef. B‡	0.161	0.125	0.060	0.003
C.V. (%)	6.87	7.64	8.80	16.06
	Sweet corn in the Andisol			
Sensitivity Coef. B	0.133	0.049	0.061	0.001
C.V. (%)	5.43	11.01	4.84	12.58
	Chinese cabbage in the Ultisol			
Sensitivity Coef. A	1.876	1.148		
Sensitivity Coef. B	0.212	0.120		
C.V. (%)	8.64	3.89		
	Chinese cabbage in the Andisol			
Sensitivity Coef. A	3.501	1.148		
Sensitivity Coef. B	0.191	0.069		
C.V. (%)	5.58	12.98		

† The recipical of slope predicted by the linear plateau model.
‡ The ratio of P extracted to P applied (slope in the fitted linear regression model).

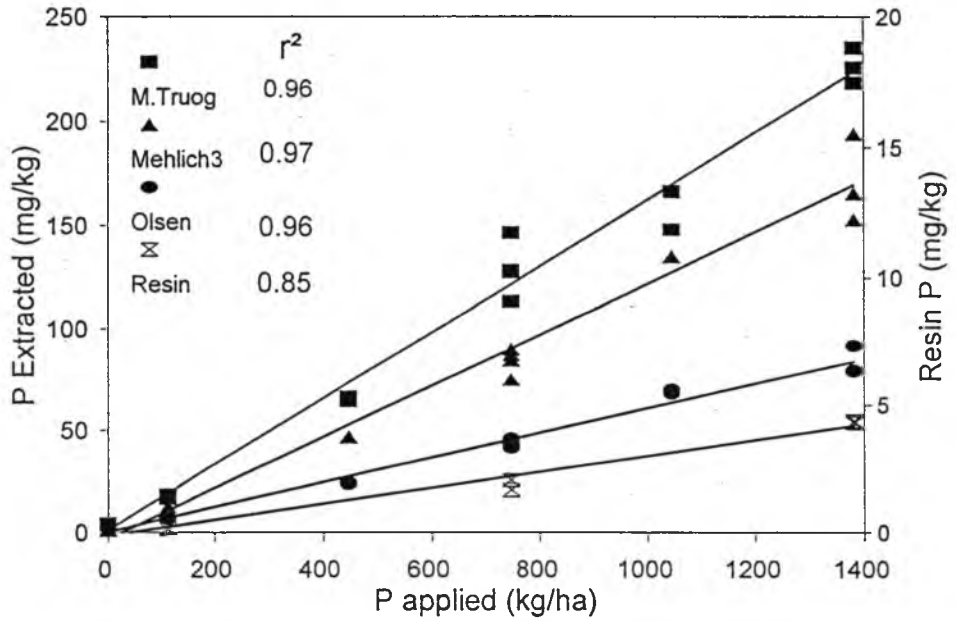

Fig. 65. Relationship between P Extracted and P Applied in the Sweet Corn Trial on an Ultisol.

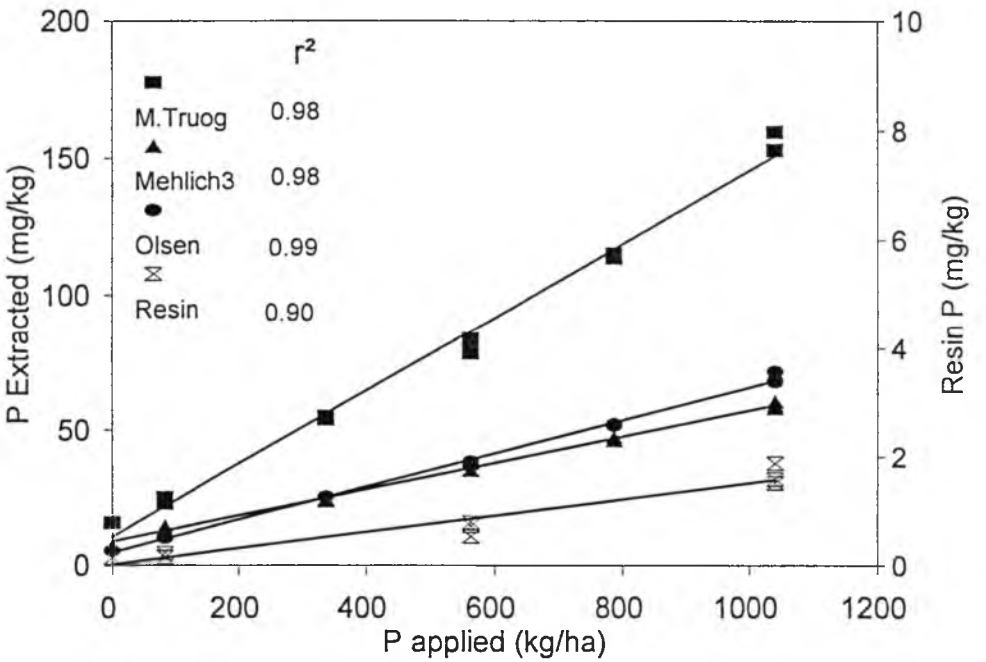

Fig. 66. Relations between P Extracted and P Applied in the Sweet Corn Trial on an Andisol.

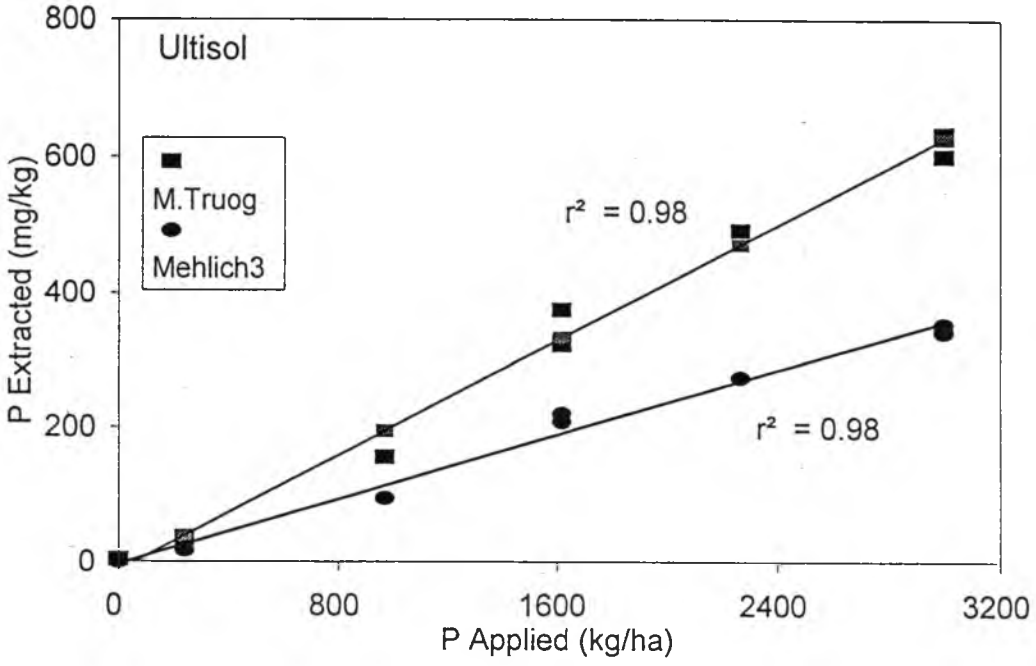

Fig. 67. Relationship between P Applied and P Extracted in the Chinese Cabbage Trial on the Ultisol.

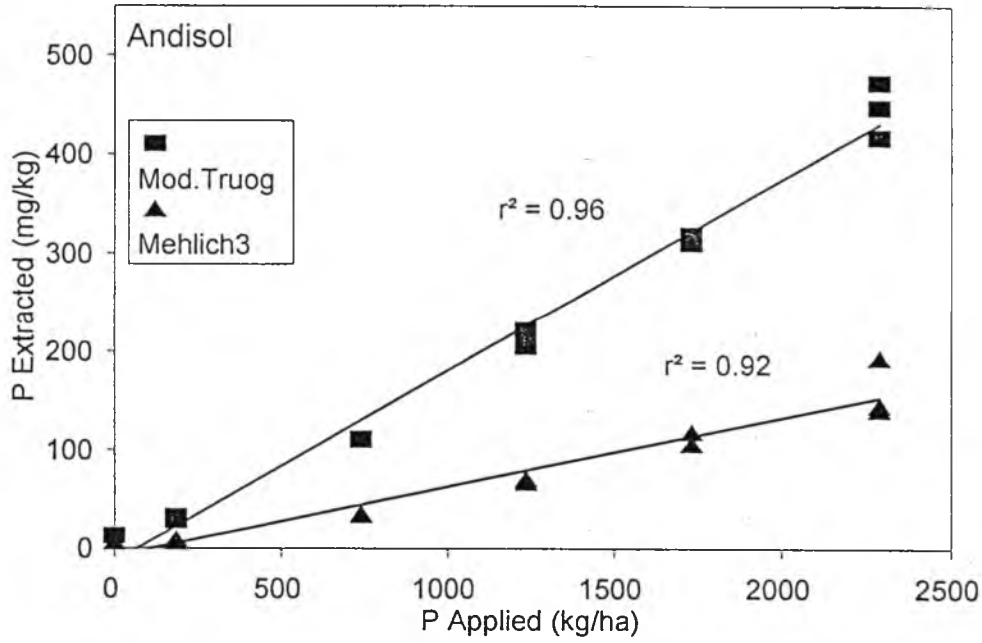

Fig. 68. Relationship between P Applied and P Extracted in the Chinese Cabbage Trial on an Andisol.

The high sensitivity of Modified Truog P might have resulted from its low ratio of soil to extractant and strong acidity. The soil-dependent nature of the sensitivity of Mehlich3 P to P applied might have been caused by reactions of some of its components, such as EDTA and F^-, with organic compounds, amorphous materials, or soil cations. Inactivation of these components could have reduced the ability of Mehlich3 to extract P from the Andisol and thus reduced its sensitivity to P applied. Sensitivity coefficient B was consistently lower in the Andisol than in the Ultisol except in the case of the Olsen method, for which it remained almost constant in the two soils. Lower values in the Andisol are generally expected because the allophane and other amorphous materials in the Andisol can absorb more P than can the Al and Fe oxides in the Ultisol (Figs. 1, 2, and 3).

Coefficient of variation for sampling: For the sweet corn trials, the Resin method produced the highest sampling error C.V.'s in both soils, while Modified Truog had the lowest values in the Ultisol and the second lowest values in the Andisol (Table 11). The C.V. from Mehlich3 was lower than that from Olsen in the Ultisol and higher than that from Olsen in the Andisol. The high C.V. values from Resin might have resulted from the very low P concentrations in the stripping solution, which could cause higher variation between samples due to contamination and/or measurement error. For the Chinese cabbage trials, the C.V. from

Mehlich3 was lower than that from Modified Truog in the Ultisol and was higher than that from Modified Truog in the Andisol.

SELECTION OF P EXTRACTION METHODS

All four P extractants were well related with plant parameters, as indicated by the coefficients of determination from the regressions of dry matter production and P uptake on P extracted, which were all 0.8 or above. The performance of Mehlich3 and Resin, which are new methods in Hawaii, was comparable in this respect to that of Modified Truog and Olsen over a wide range of P levels in both soils for both crops (Table 12). Test values from all four methods were very well correlated with one another, with Resin P being slightly less well correlated than the other three (Table 13). In the sweet corn trials, Olsen P performed best overall in terms of accuracy of diagnoses, sensitivity of test values to changes in soil P levels, and C.V. for sampling; Mehlich3 usually ranked between Olsen and Modified Truog, while Resin performed worst overall. In the Chinese cabbage trials, where only Modified Truog and Mehlich3 were tested, the performance of the two methods was comparable based on the above criteria (Tables 10 and 11). These results suggest that Mehlich3 is a feasible alternative to Modified Truog and Olsen for the tested soils and crops.

Table 12. Summary of Coefficients of Determination for the Relationships between P Extracted and Plant Parameters.†

Extractant	Dry matter	P uptake	Tissue P
	Sweet corn in the Ultisol		
Mod. Truog	0.96	0.87	0.66
Mehlich3	0.97	0.93	0.71
Olsen	0.98	0.91	0.68
Resin	0.96	0.93‡	0.87‡
	Sweet corn in the Andisol		
Mod. Truog	0.89	0.90	0.86
Mehlich3	0.80	0.82	0.88
Olsen	0.84	0.84	0.88
Resin	0.82	0.85	0.93‡
	Chinese cabbage in the Ultisol		
Mod. Truog	0.90	0.92	0.94
Mehlich3	0.91	0.93	0.96
	Chinese cabbage in the Ultisol		
Mod. Truog	0.89	0.93	0.90
Mehlich3	0.88	0.92	0.89

† All regression equations for dry matter relationships consisted of the following terms: P extracted, $(P\ extracted)^2$, K added, $(K\ added)^2$, and (P extracted) *(K added). For the Chinese cabbage trials, equations for tissue P and P uptake relationships consisted of the terms P extracted and $(P\ extracted)^2$. For the sweet corn trials, equations for tissue P and P uptake relationships (other than those with coefficients of determination followed by a '‡') included only P extracted.

‡ Regression equations for these relationships included P extracted and $(P\ extracted)^2$.

Table 13. Summary of r Values for the Correlations between P Extraction Methods.

	Mod. Truog	Mehlich3	Olsen
	Sweet corn in the Ultisol		
Mehlich3	0.95**†	-	-
Olsen	0.96**	0.96**	-
Resin	0.92**	0.89**	0.94**
	Sweet corn in the Andisol		
Mehlich3	0.98**	-	-
Olsen	0.99**	0.98**	-
Resin	0.94**	0.94**	0.95**
	Chinese cabbage in the Ultisol		
Mehlich3	0.99**	-	
	Chinese cabbage in the Andisol		
Mehlich3	0.98**	-	

† Highly significant (α = 0.01).

Evaluation of K Extraction Methods

THE RELATIONSHIP BETWEEN K APPLIED AND K EXTRACTED AT PLANTING

The analysis of soil samples that were incubated with applied K, which were considered to represent the soil K status at planting, showed that there was a close relationship between K extracted by NH_4OAc and Mehlich3 and K applied in both soils, with r^2 values of about 0.99 (Figs. 69 and 70). A similar relationship was found between Resin K and K applied in the Ultisol (Fig. 69).

THE RELATIONSHIP BETWEEN K APPLIED AND K EXTRACTED AFTER ONE MONTH

For sweet corn trials, the relationships between K applied and K extracted by NH_4OAc, Mehlich3, and Resin from the soil samples collected after harvest were good only at the lowest P application rates (where r^2 values were greater than or equal to 0.8) (Table 14). At the higher P application rates there was very little increase in K extracted with K applied. High K uptake values, which generally were comparable to or greater than the values for K applied at these P levels, are mainly responsible for this result (Fig. 71-74). The relationships between K extracted and K applied and between K extracted and K expected (initial K + Kapplied - K uptake) were consistently poorer in the Ultisol than in the Andisol (Table 14 and Figs. 71-74).

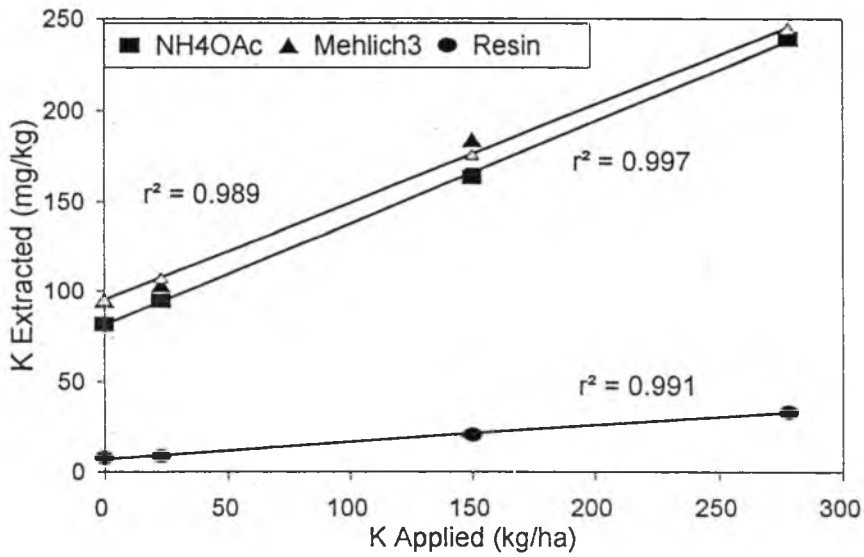

Fig. 69. Relationship between K Applied and K Extracted from an Ultisol after a One-Week Incubation.

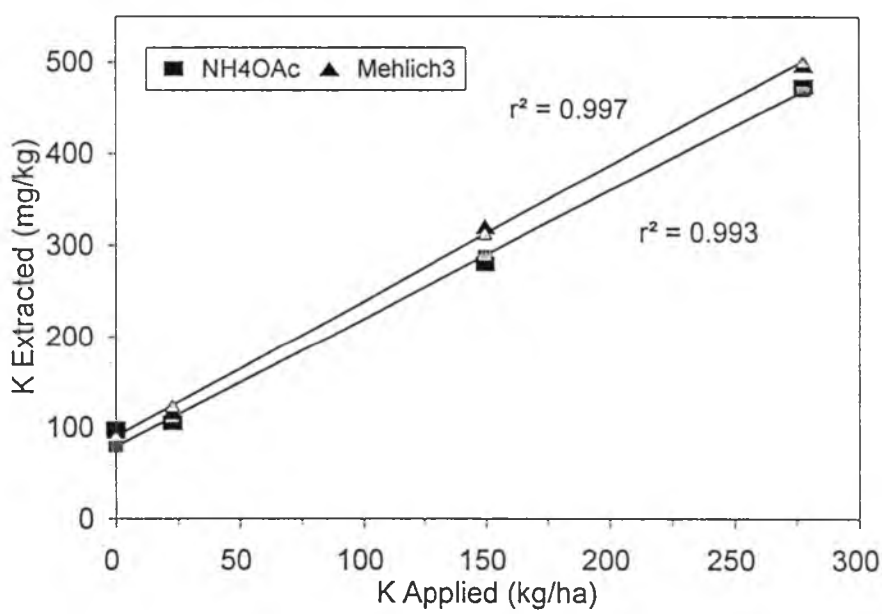

Fig. 70. Relationship between K Applied and K Extracted by NH4OAc and Mehlich3 from an Andisol after a One-Week Incubation.

Table 14. The r^2 Values for the Relationships between K Applied and K Extracted at Three P Levels after a One-Month Sweet Corn Trial.

P applied (kg/ha)	NH_4OAc K	Mehlich3 K	Resin K
		Ultisol	
112	0.91	0.80	0.89
747	0.59	0.19	0.20
1382	0.23	0.63	0.22
		Andisol	
84	0.98	0.97	0.97
563	0.64	0.57	0.50
1041	0.56	0.56	0.58

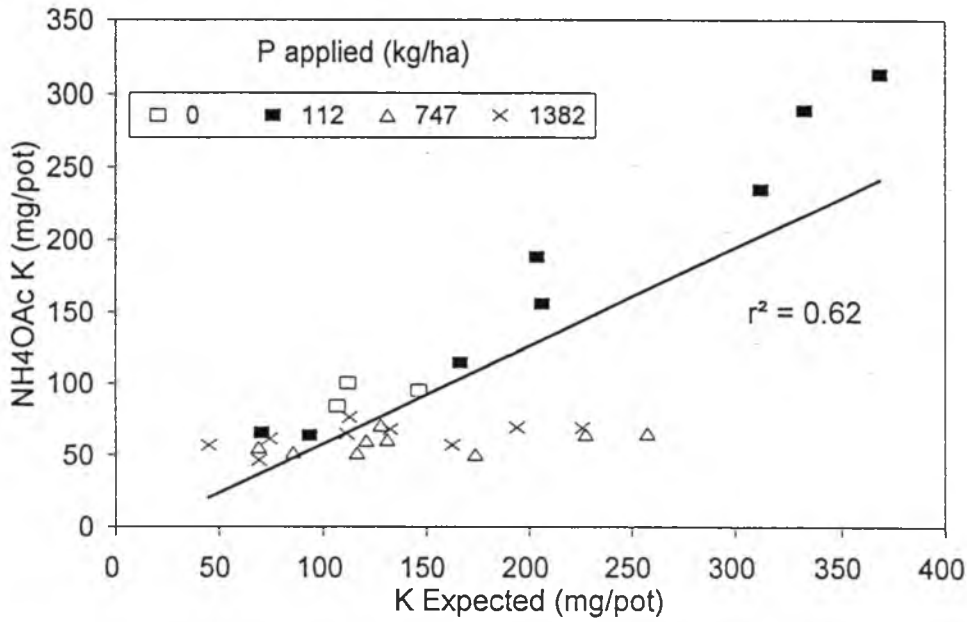

Fig. 71. Relationship between K Expected (initial K + K added - K uptake) and K Extracted by NH4OAc after a One-month Sweet Corn Trial in an Ultisol.

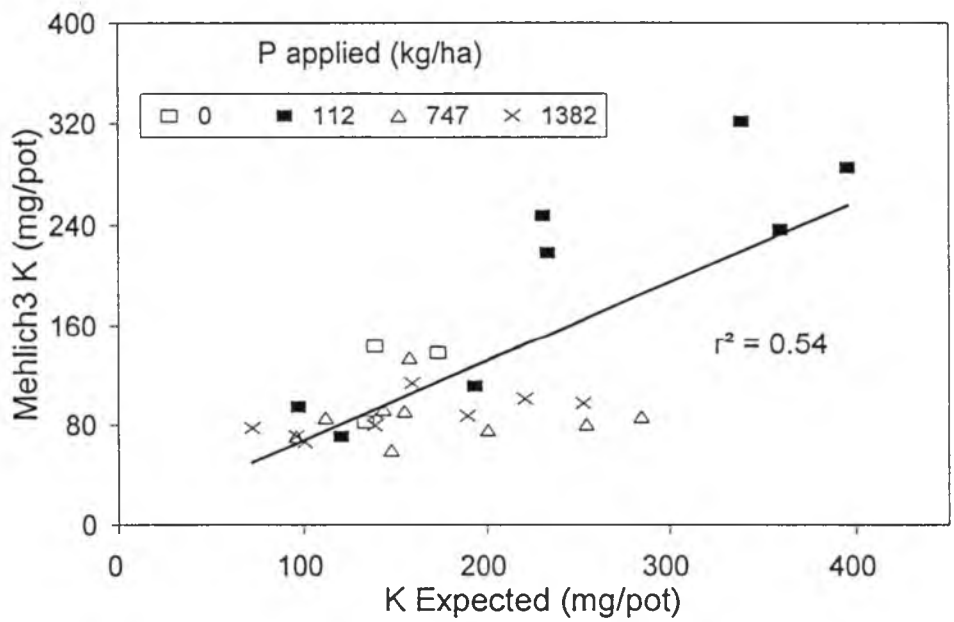

Fig. 72. Relationship between K Expected (initial K + K added - K uptake) and K Extracted by Mehlich3 after a One-Month Sweet Corn Trial in an Ultisol.

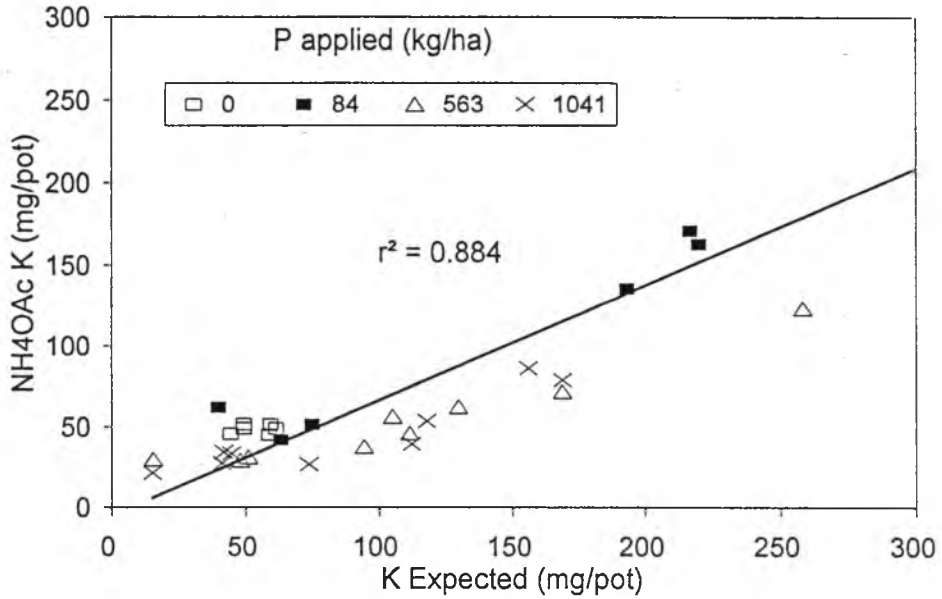

Fig. 73. Relationship between K Expected (initial K + K added - K uptake) and K Extracted by NH4OAc after a One-month Sweet Corn Trial in an Andisol.

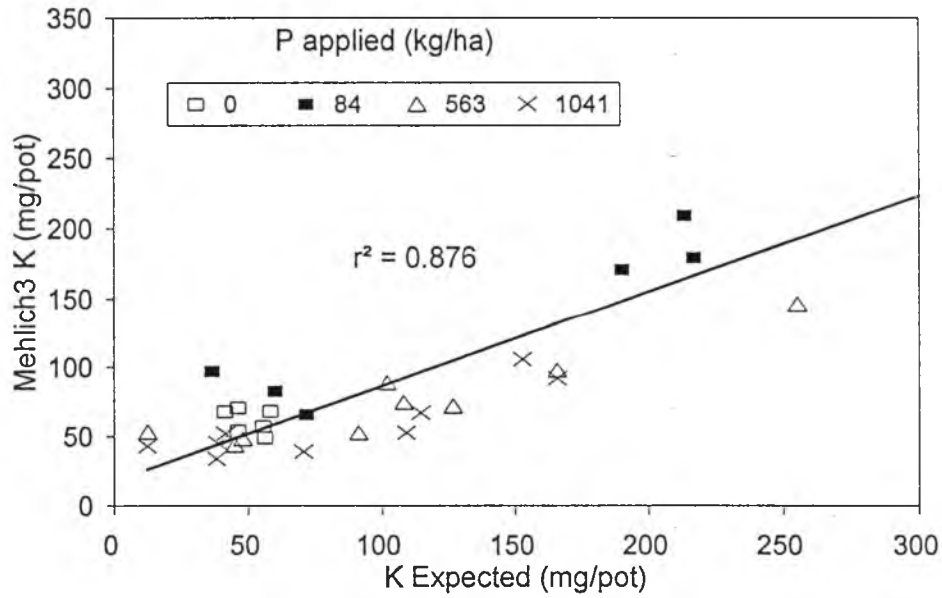

Fig. 74. Relationship between K Expected (initial K + K added - K uptake) and K Extracted by Mehlich3 after a One-month Sweet Corn Trial in an Andisol.

On the contrary, the relationships between K extracted and K applied and between K extracted and K expected (initial K + Kapplied - K uptake) were much poorer in the Andisol than in the Ultisol for Chinese cabbage trials. There was a good relationship between Mehlich3 K from soil samples collected after harvest and K applied at the lowest P level in the Ultisol (r^2 = 0.87). However, the coefficients of single determination for the regression between K applied and Mehlich3 K after harvest of Chinese cabbage in the Andisol were 0.37 or less at all P levels. The r^2 value for the regression between Mehlich3 K and K expected was 0.73 for the Ultisol and 0.23 for the Andisol (Figs. 75 and 76). The reasons for these differences are unknown.

THE RELATIONSHIPS BETWEEN K EXTRACTED AND PLANT PARAMETERS AND BETWEEN K EXTRACTION METHODS IN SWEET CORN TRIALS

K Extracted at Planting versus Dry Matter, Tissue K, and K Uptake: The relationships between sweet corn dry matter and K extracted by NH_4OAc, Mehlich3, and Resin were almost identical to the relationship between dry matter and K applied in the Ultisol (Figs. 77-79). The relationships between dry matter and K extracted by NH_4OAc and Mehlich3 in the Andisol were also similar to that between dry matter and K applied (Figs. 80 and 81). There was a close relationship between tissue K and K extracted by NH_4OAc, Mehlich3 and Resin in the Ultisol at P application rates of 112 and 1382 kg/ha. The relationship between K extracted and tissue K was much

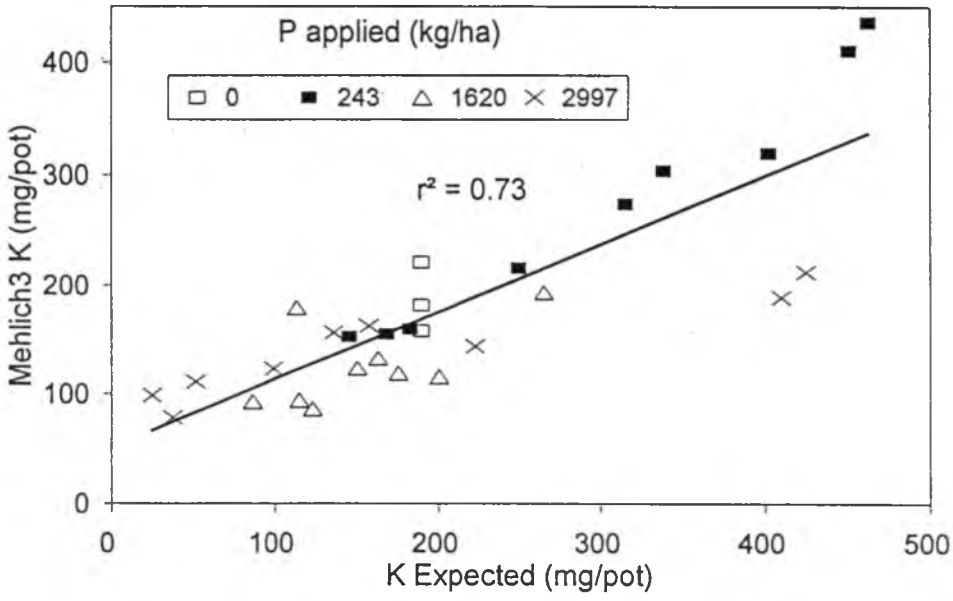

Fig. 75. Relationship between K Expected (initial K + K added - K uptake) and K Extracted by Mehlich3 after a One-month Chinese Cabbage Trial in an Ultisol.

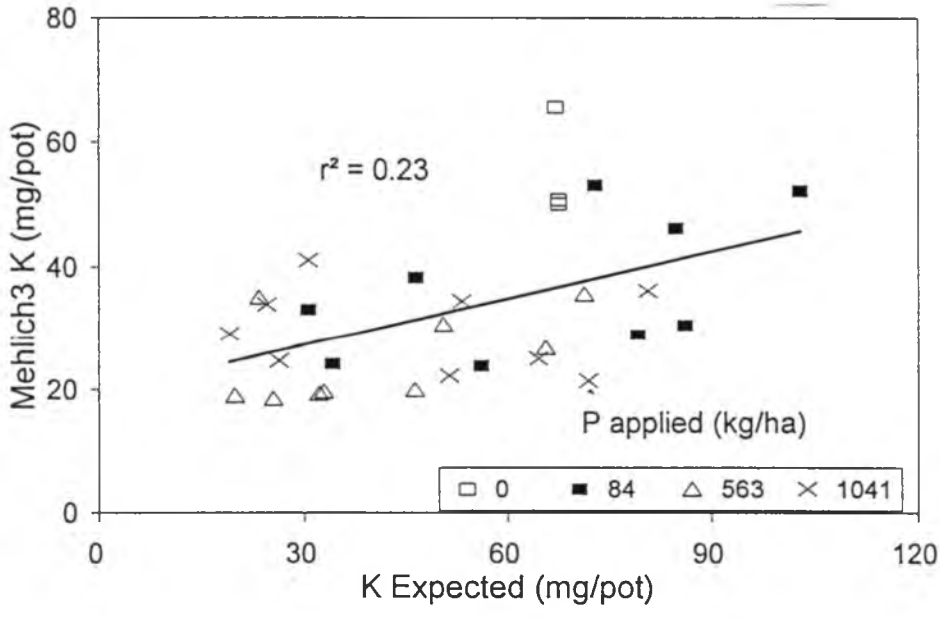

Fig. 76. Relationship between K Expected (initial K + K added - K uptake) and K Extracted by Mehlich3 after a One-month Chinese Cabbage Trial in an Andisol.

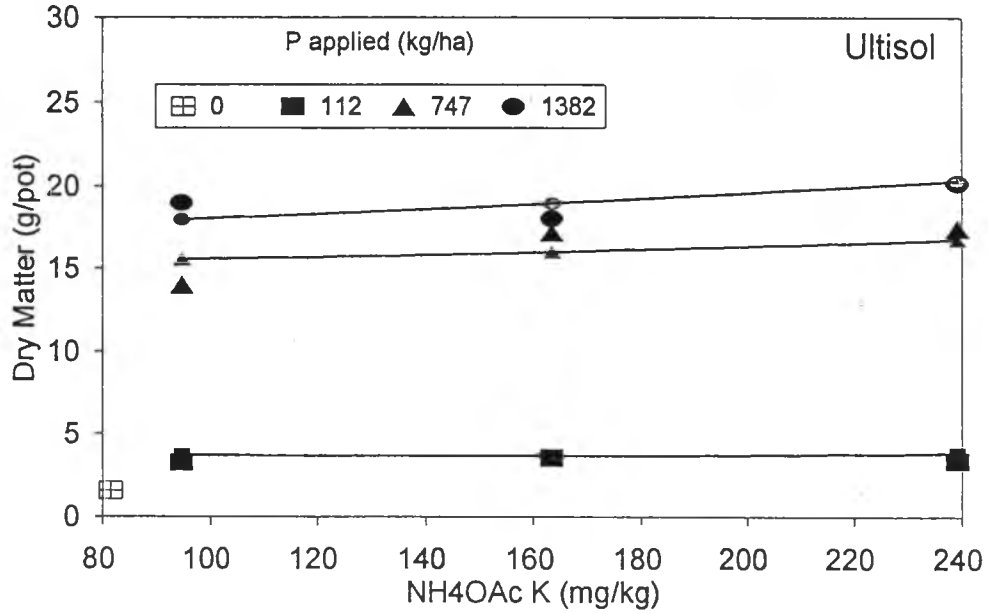

Fig. 77. Response of Sweet Corn Dry Matter Yield to NH4OAc K Extracted after a One-Week Incubation in an Ultisol.

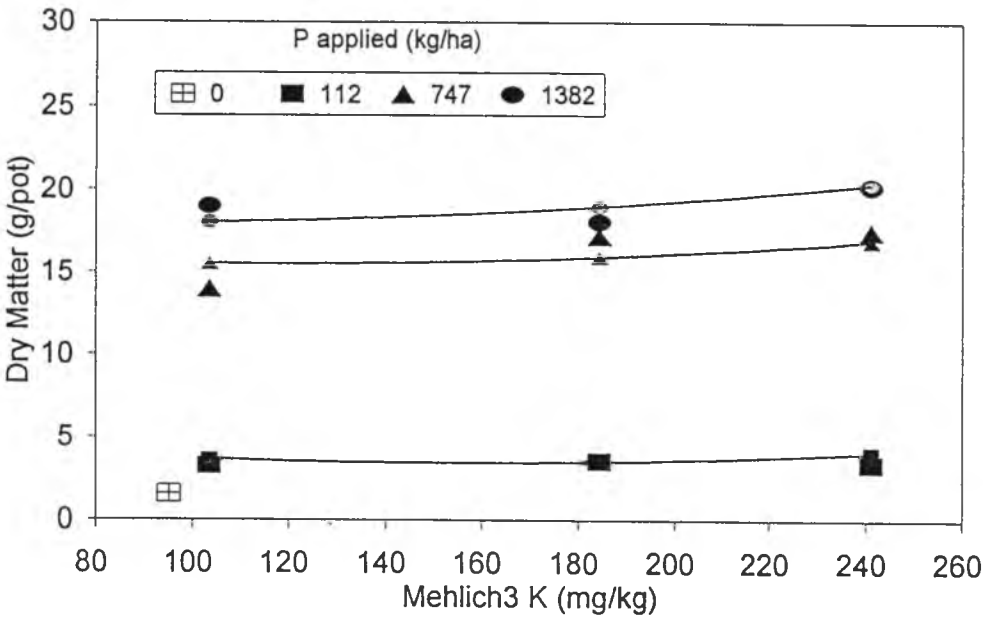

Fig. 78. Response of Sweet Corn Dry Matter Yield to Mehlich3 K Extracted after a One-Week Incubation in an Ultisol.

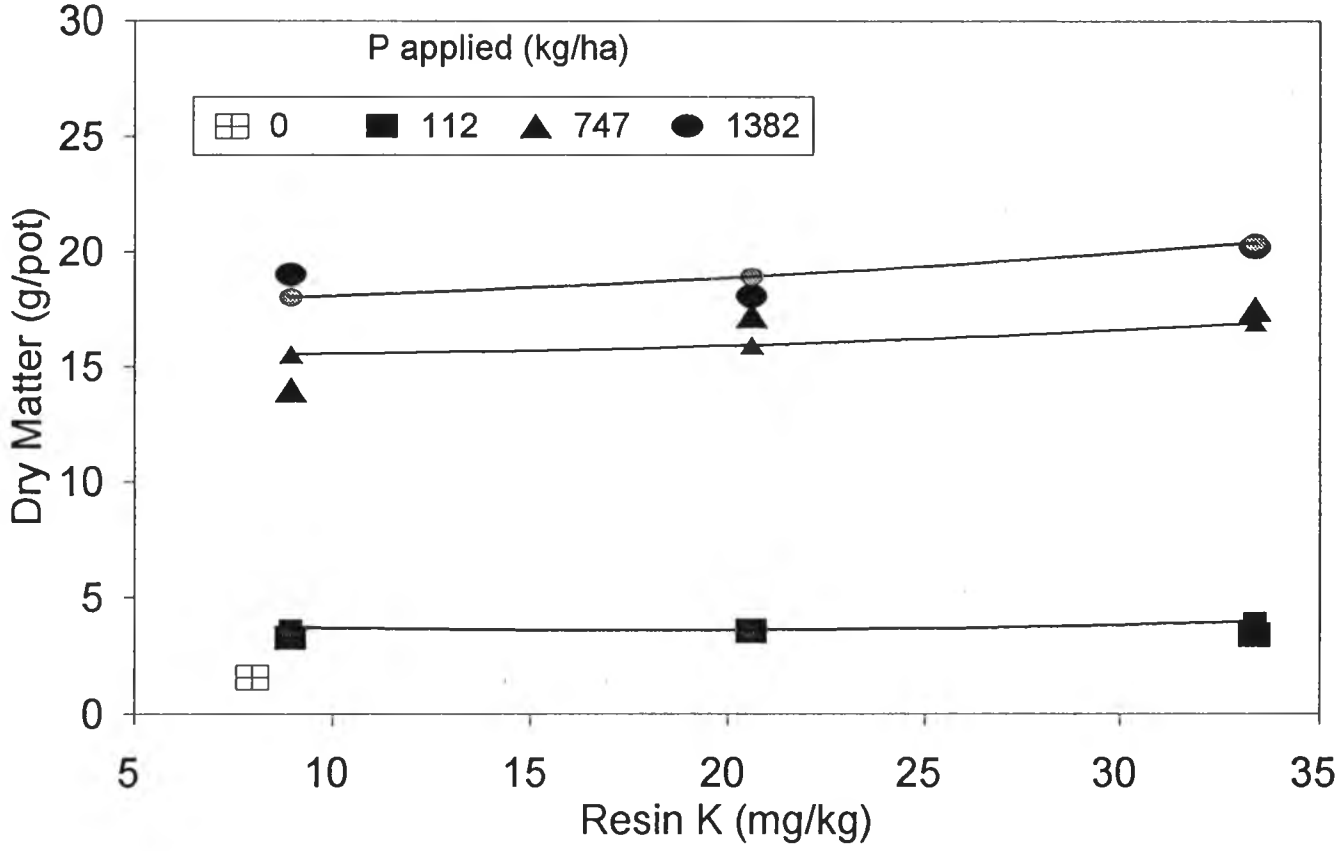

Fig. 79. Response of Sweet Corn Dry Matter Yield to Resin K Extracted after a One-Week Incubation in an Ultisol.

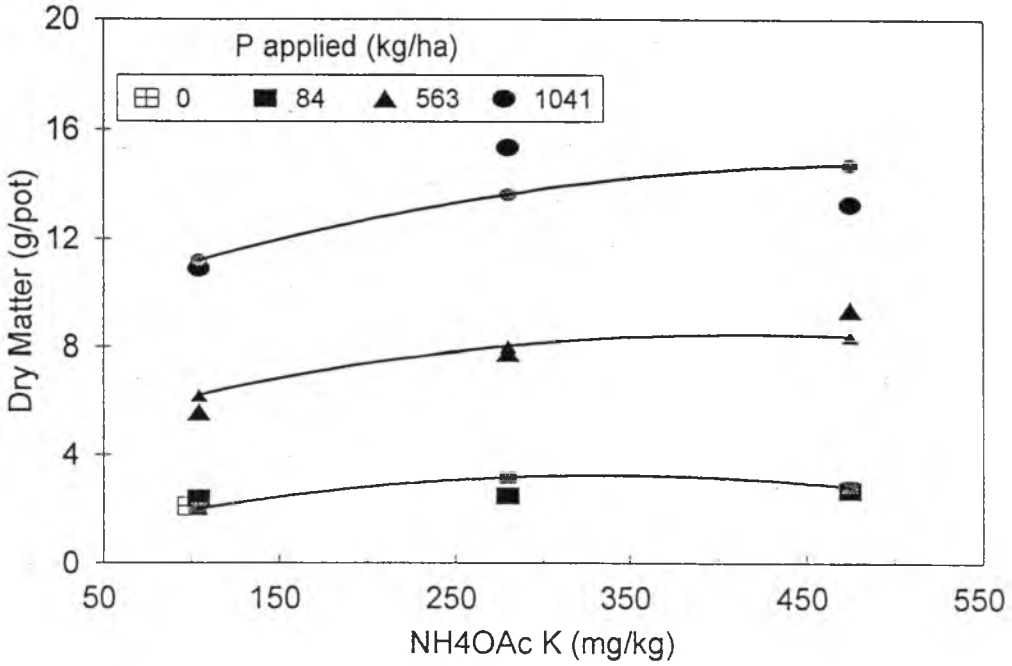

Fig. 80. Response of Sweet Corn Dry Matter Yield to NH4OAc K in an Andisol.

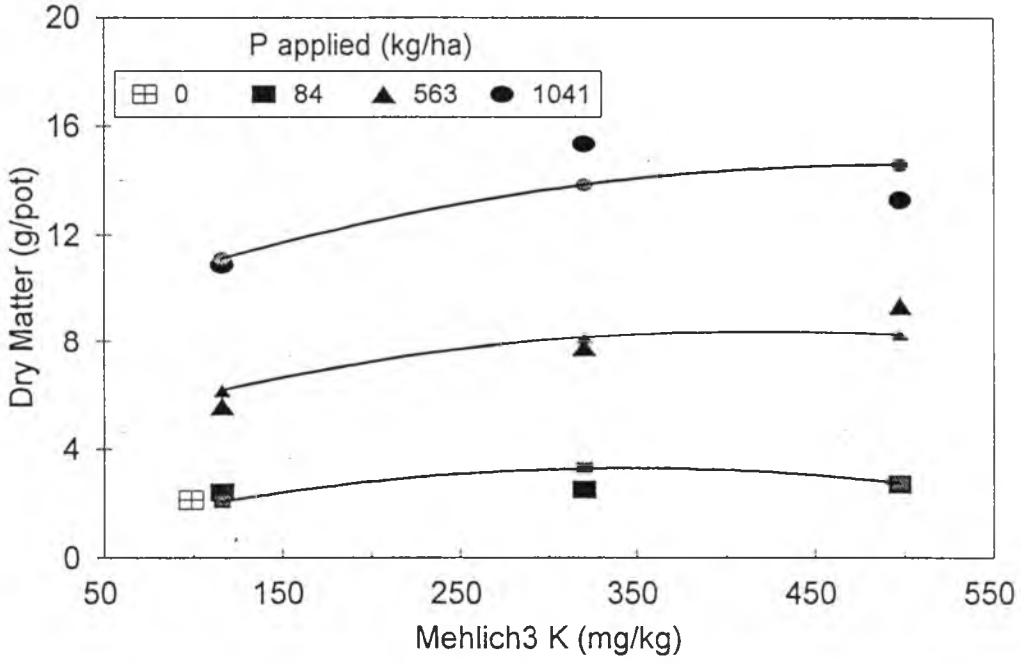

Fig. 81. Response of Sweet Corn Dry Matter Yield to Mehlich3 K in an Andisol.

poorer at the middle P application rate of 747 kg/ha (Figs. 82-84). This might have been caused by the variation in the dilution of plant K concentrations, which was observed to be greatest at the middle P level. In the Andisol, the coefficient of single determination for tissue K and K extracted by NH_4OAc and Mehlich3 ranged from 0.73 to 0.90 at all three P levels (Figs. 85 and 86). However, the highest r^2 was found at the lowest P level, where less dilution of plant K concentrations caused by P applications would be expected (Figs. 85 and 86).

Regressions of sweet corn K uptake on K extracted by NH_4OAc, Mehlich3, and Resin in the Ultisol were highest in the middle and highest P levels in this soil (Figs. 87-89). At all P levels, the relationships between K uptake and K extracted by NH_4OAc and Mehlich3 were much better in the Andisol than were those in the Ultisol (Figs. 90 and 91). It is interesting to note that the relationship was also better at the middle and highest of P levels than the lowest P level in the Andisol. This might again be due to higher potentially available K in the Ultisol, which became accessible to the plants slowly over the course of the trials but which was not released by a one-time exposure to these extractants.

Relationships between K Uptake and the Change in K Extracted during the One-Month Trials: For NH_4OAc and Mehlich3 in both soils, sweet corn K uptake was linearly

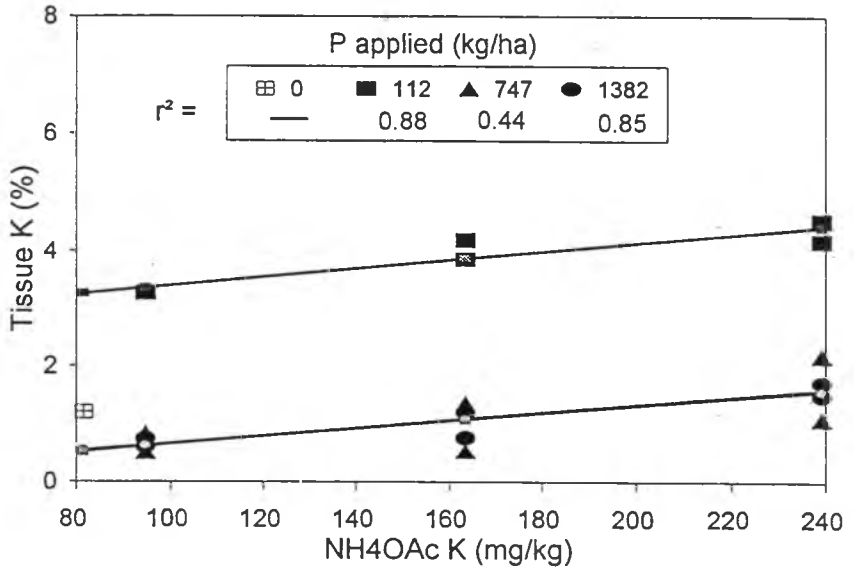

Fig. 82. Relationship between Sweet Corn Tissue K Concentration and K Extracted by NH4OAc from an Ultisol after a One-Week Incubation.

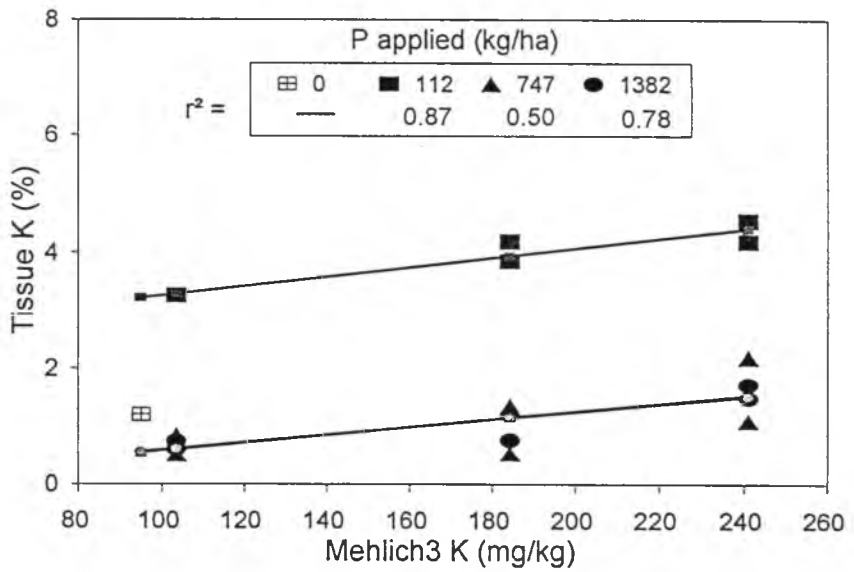

Fig. 83. Relationship between Sweet Corn Tissue K Concentration and K Extracted by Mehlich3 from an Ultisol after a One-Week Incubation.

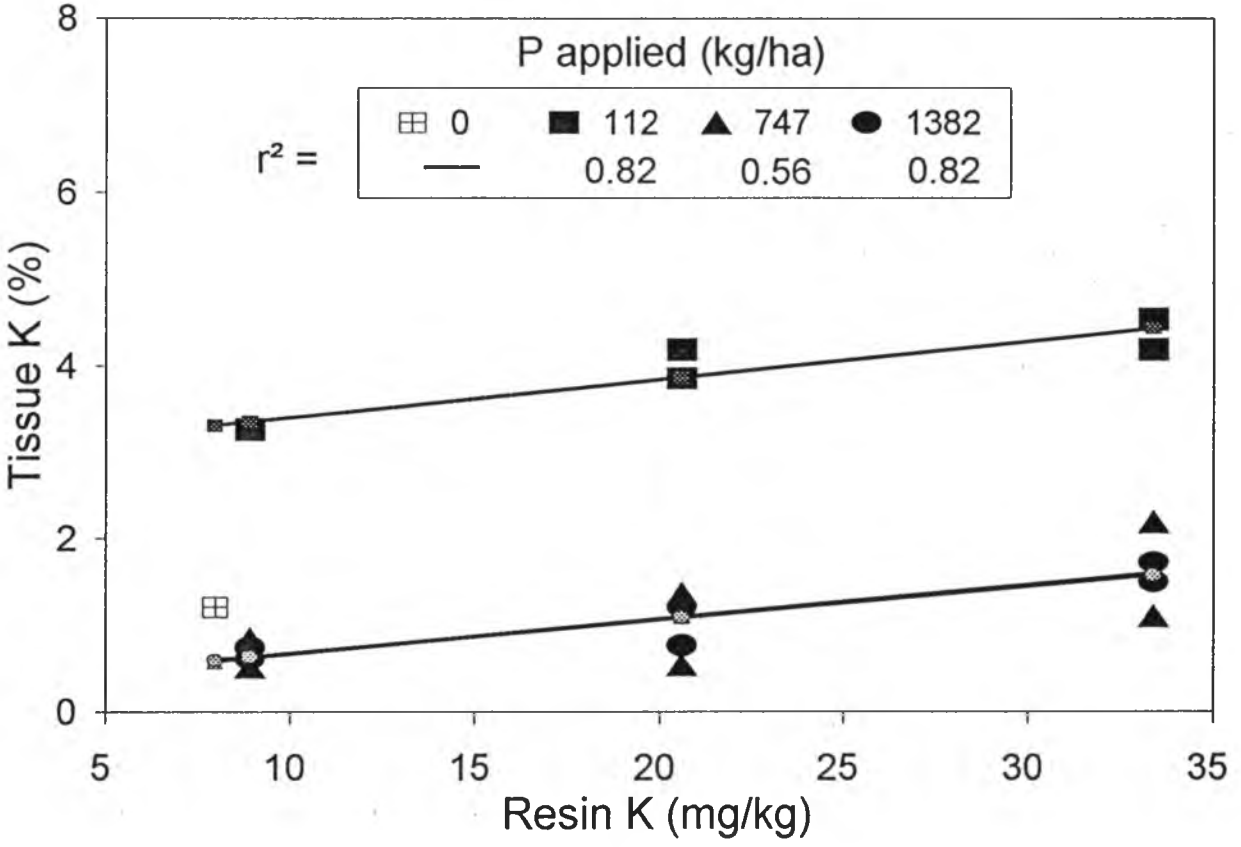

Fig. 84. Relationship between Sweet Corn Tissue K Concentration and K Extracted by Resin from an Ultisol after a One-Week Incubation.

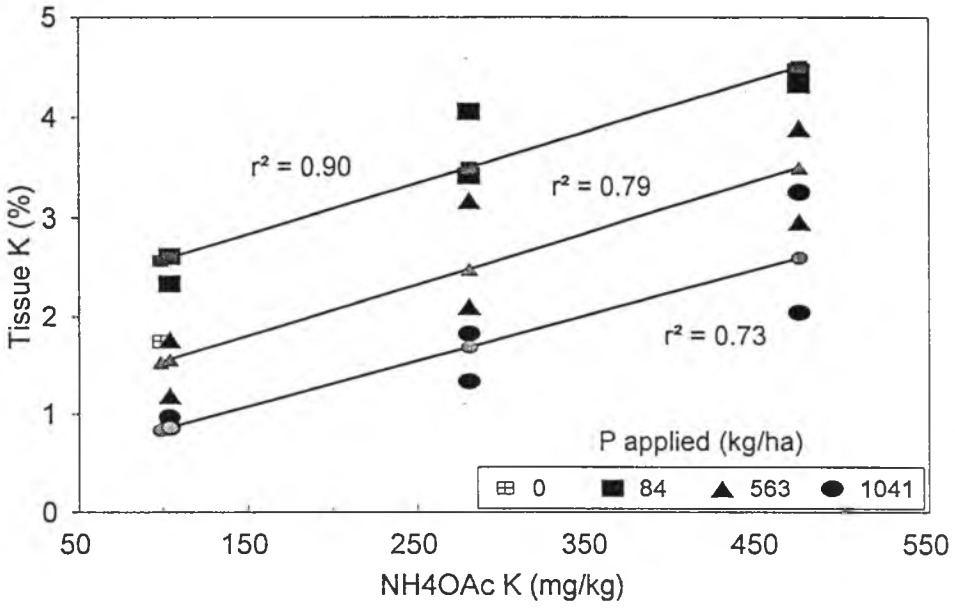

Fig. 85. Relationship between Sweet Corn Tissue K Concentration and K Extracted by NH4OAc from an Andisol after a One-Week Incubation.

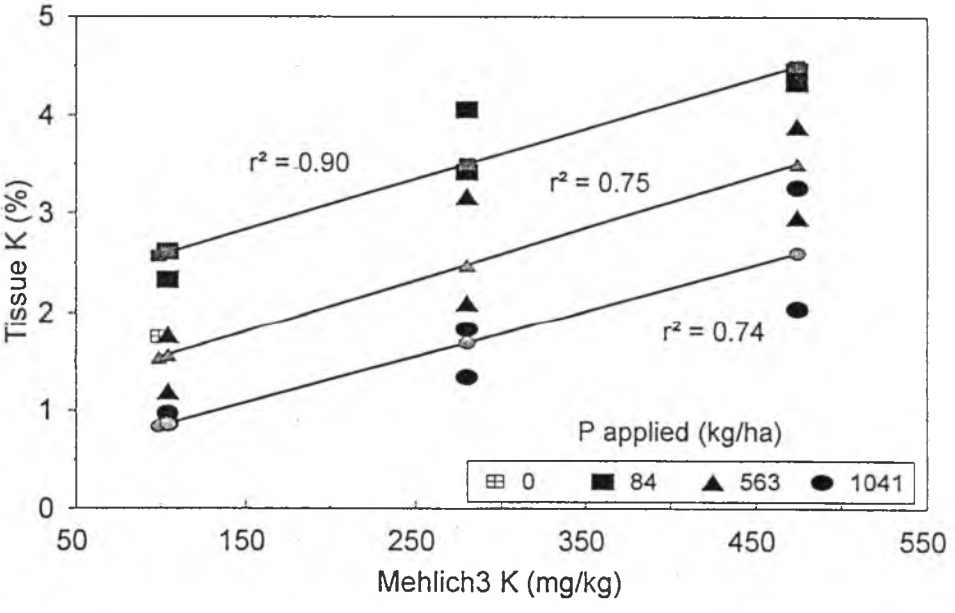

Fig. 86. Relationship between Sweet Corn Tissue K Concentration and K Extracted by Mehlich3 from an Andisol after a One-Week Incubation.

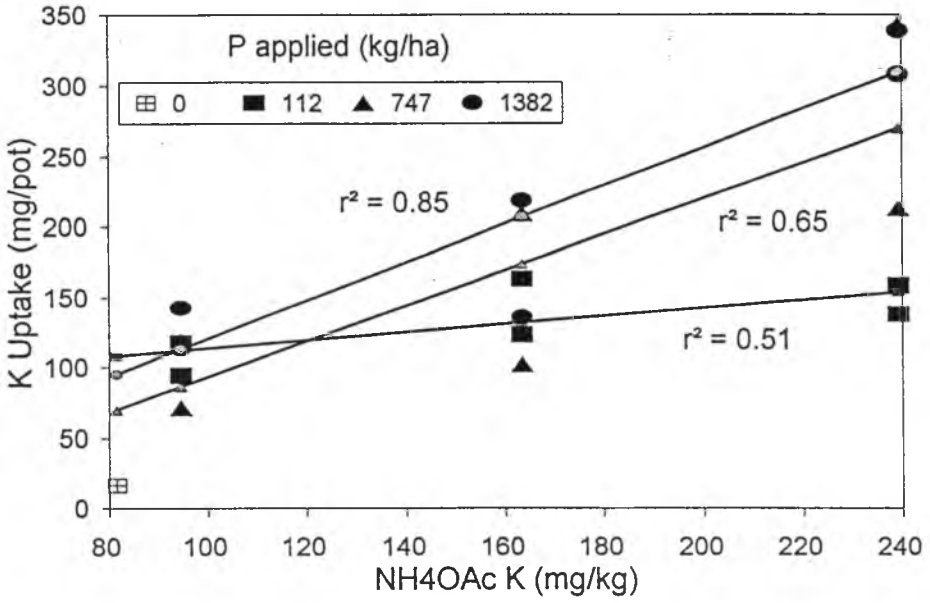

Fig. 87. Relationship between K Extracted by NH4OAc after a One-Week Incubation and Sweet Corn K Uptake in an Ultisol.

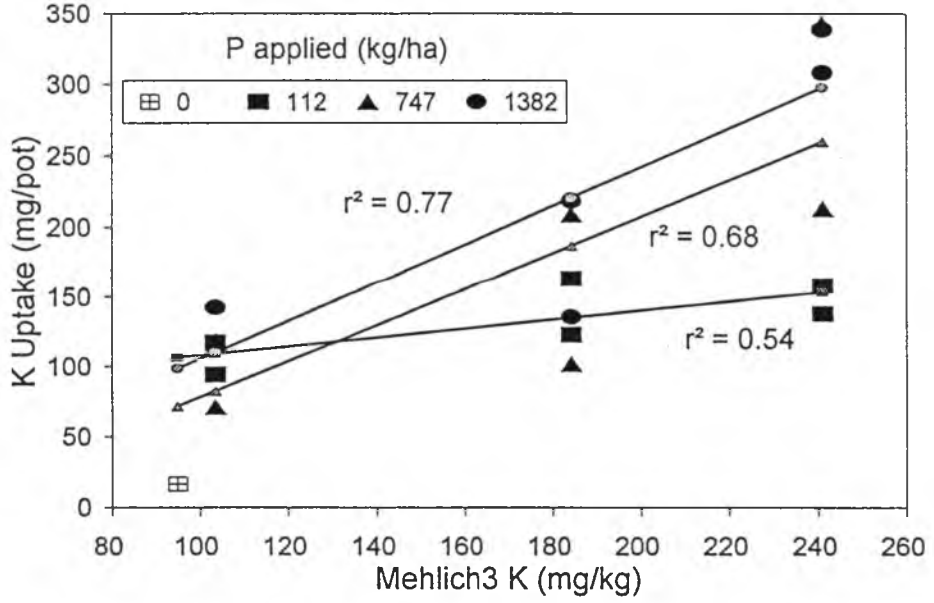

Fig. 88. Relationship between K Extracted by Mehlich3 after a One-Week Incubation and Sweet Corn K Uptake in an Ultisol.

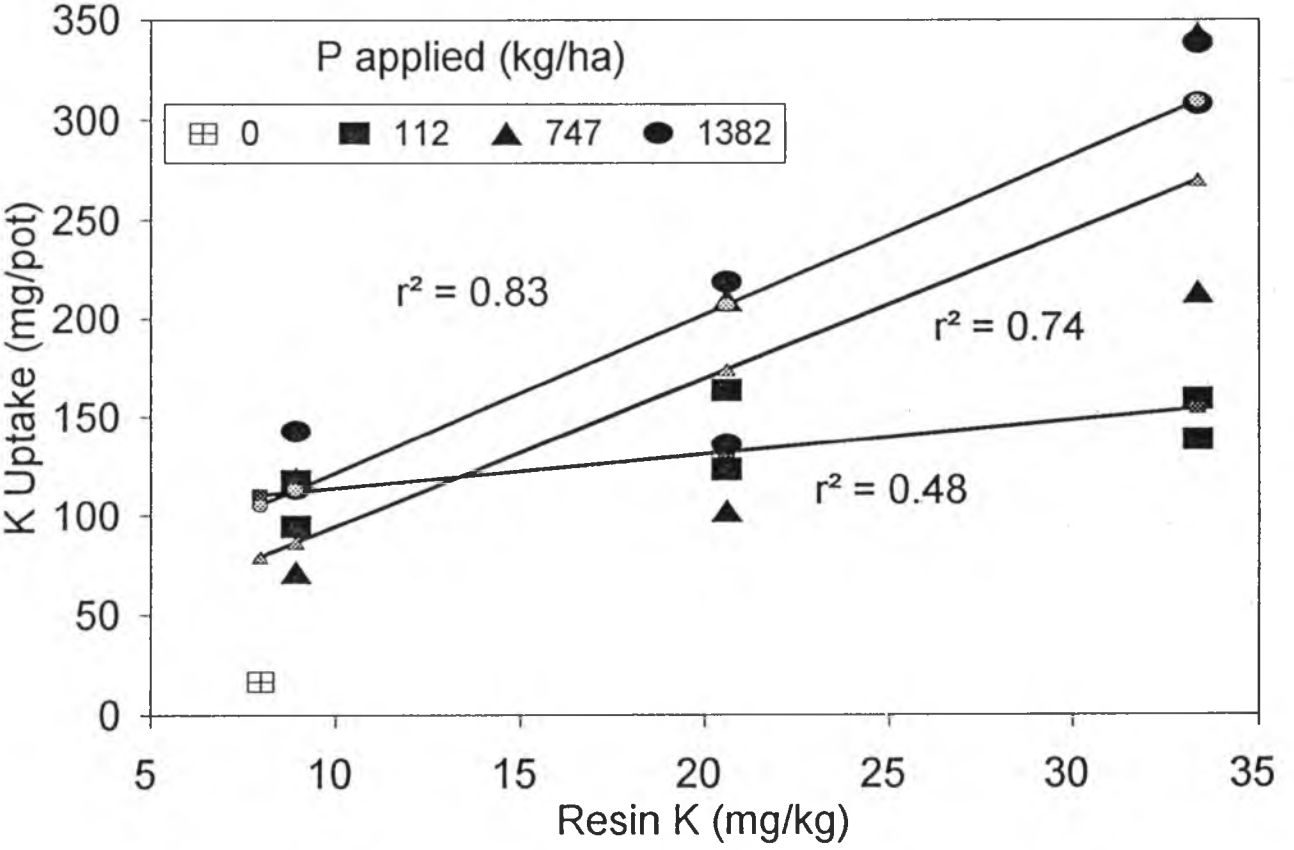

Fig. 89. Relationship between K Extracted by Resin after a One-Week Incubation and Sweet Corn K Uptake in an Ultisol.

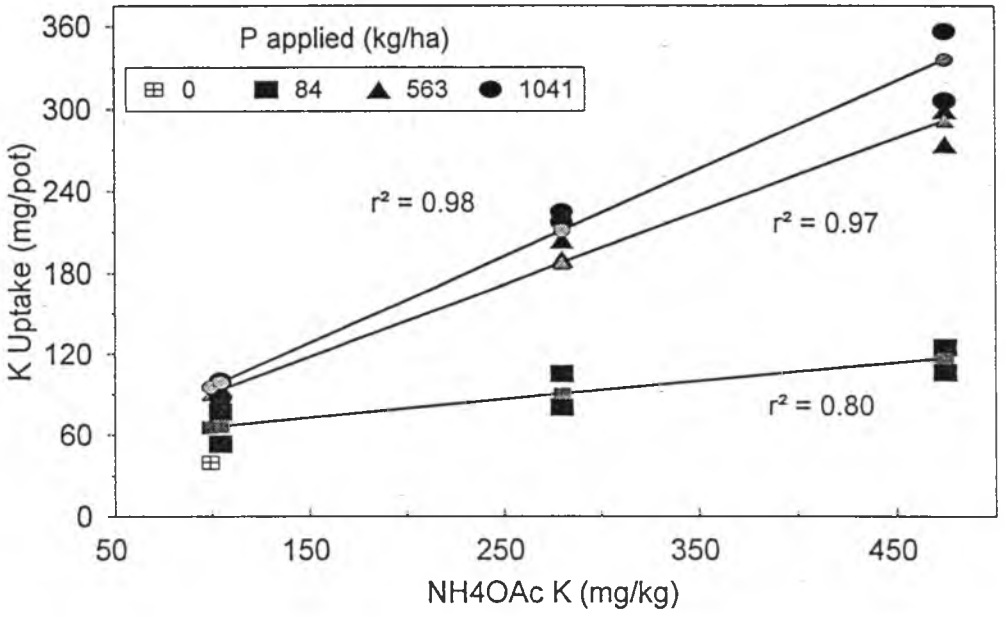

Fig. 90. Relationship between K Extracted by NH4OAc after a One-Week Incubation and Sweet Corn K Uptake in an Andisol.

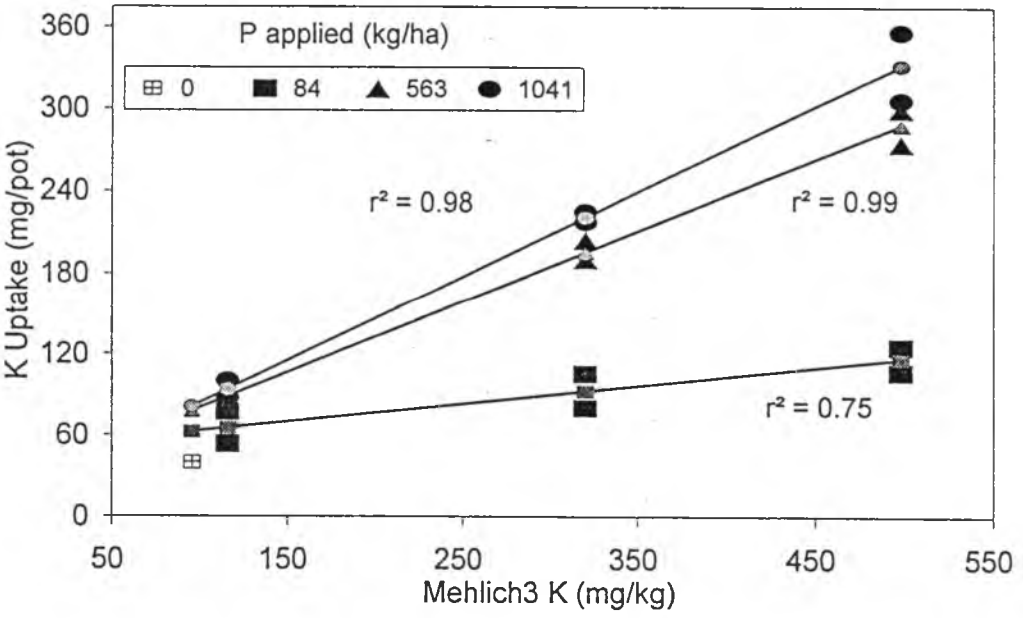

Fig. 91. Relationship between K Extracted by Mehlich3 after a One-Week Incubation a Sweet Corn K Uptake in an Andisol.

related with the difference between K extracted after and K extracted before the one-month trials. However, these relationships were again much closer in the Andisol than in the Ultisol, with r^2 values of 0.79 and 0.74 for NH_4OAc and Mehlich3, respectively, in the Ultisol, and r^2 values of 0.95 and 0.92 in the Andisol (Figs. 92-94). This difference is understandable because K uptake was not as well related with K extracted or K applied in the Ultisol as it was in the Andisol. The lowest r^2 value (0.63) for the relationship between K uptake and the change in K extracted was obtained for Resin K in the Ultisol (Fig. 95). Using air-dried soil samples for the Ultisol after the one-month trial might have had a greater effect on results from the Resin method than on those from the other two methods. The Resin method is designed for use with field-moist soil samples (Yang et al. 1990). However, the potential effect of using air-dry soil on the extraction results is unknown.

For the soils analyzed immediately after incubation, the correlations between K extraction methods were very high in both soils, with all r values greater than 0.98 (Figs. 96 and 97). Similarly strong correlations between these methods were obtained from Andisol samples collected after the one-month trial (Fig. 98). For samples collected after the one-month trial in the Ultisol, the r values for the correlations between the three methods were much lower than those derived from soil samples analyzed right after incubation (Fig. 99).

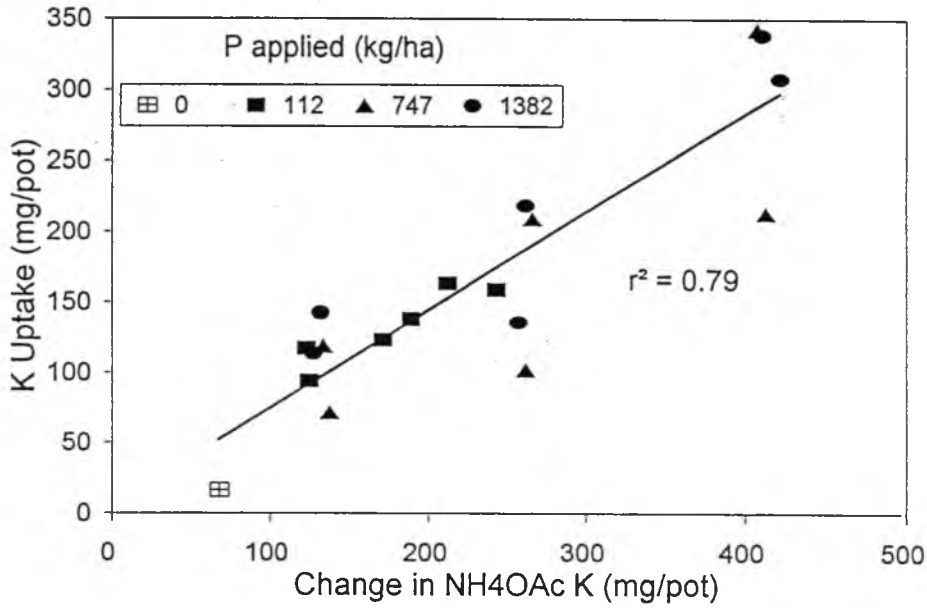

Fig. 92. Relationship between Plant K Uptake and the Change in NH4OAc K during a One-Month Sweet Corn Trial in an Ultisol.

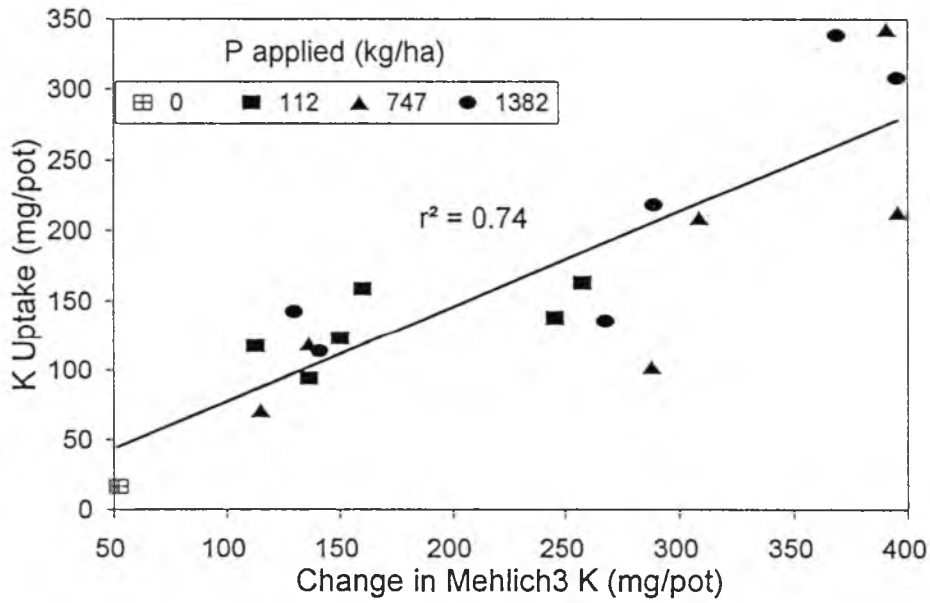

Fig. 93. Relationship between Plant K Uptake and the Change in Mehlich3 K during One-Month Sweet Corn Trial in an Ultisol.

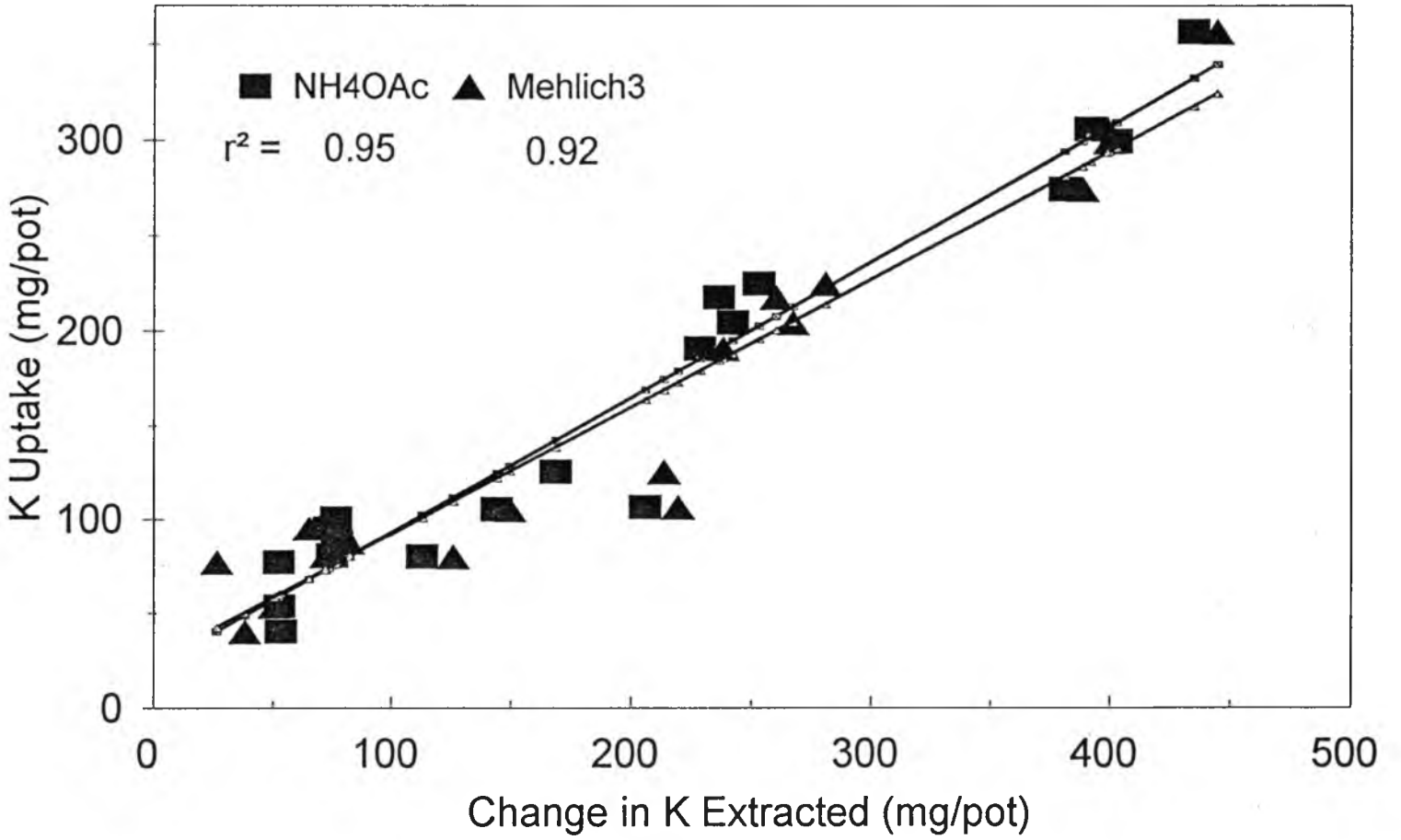

Fig. 94. Relationship between K Uptake and the Change in NH4OAc K and in Mehilch3 K during a One-Month Sweet Corn Trial in an Andisol.

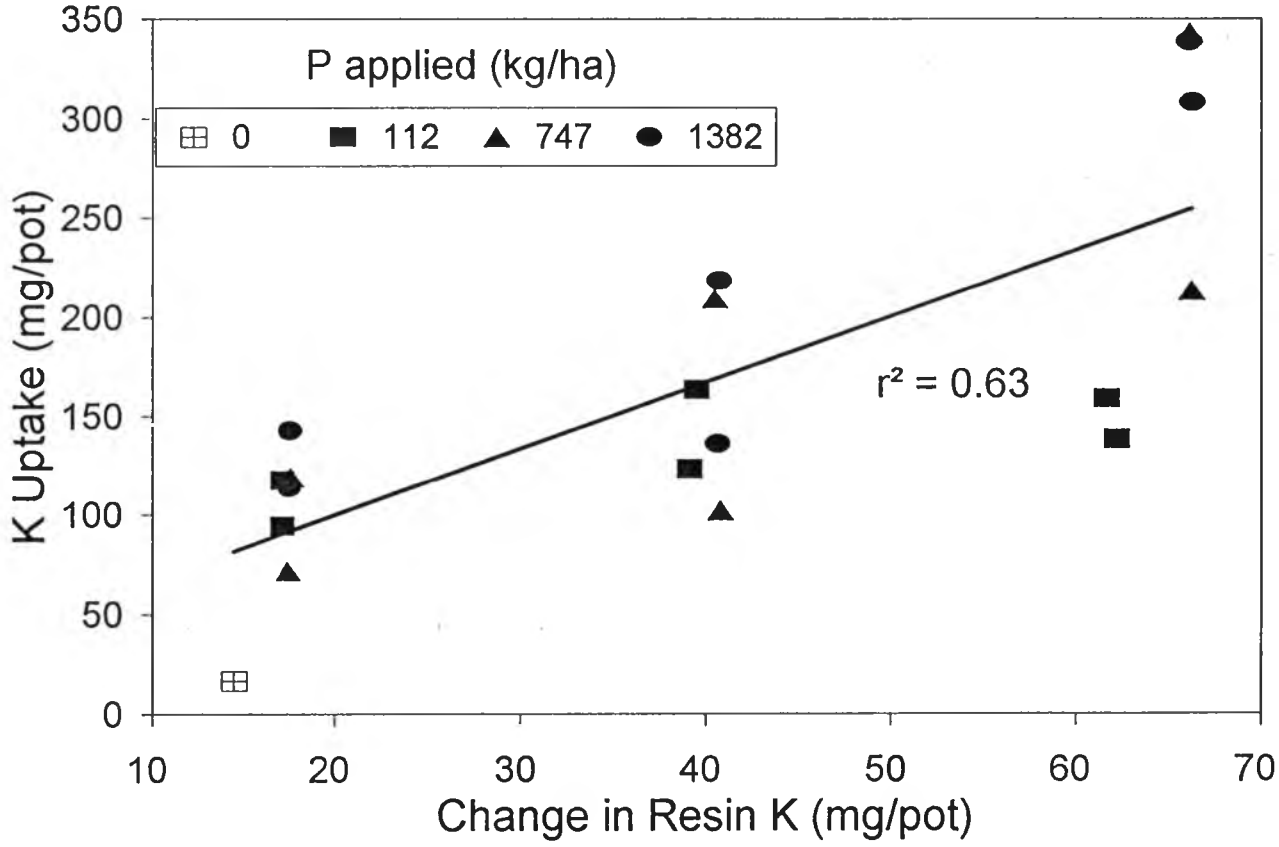

Fig. 95. Relationship between Plant K Uptake and the Change in Resin K during a One-Month of Sweet Corn Trial in an Ultisol.

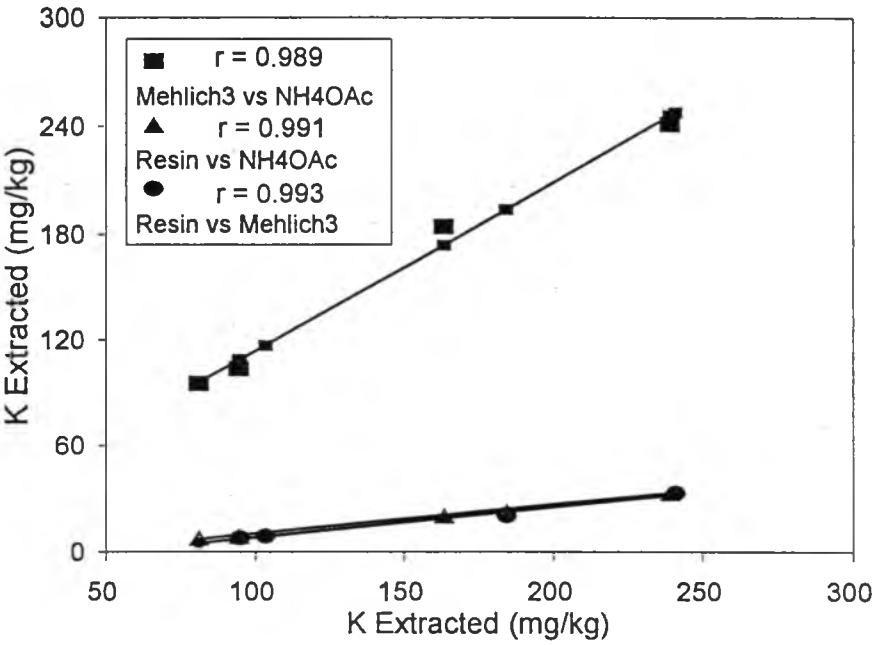

Fig. 96. Correlations between K Extracted by Three Methods from an Ultisol after a One-Week Incubation.

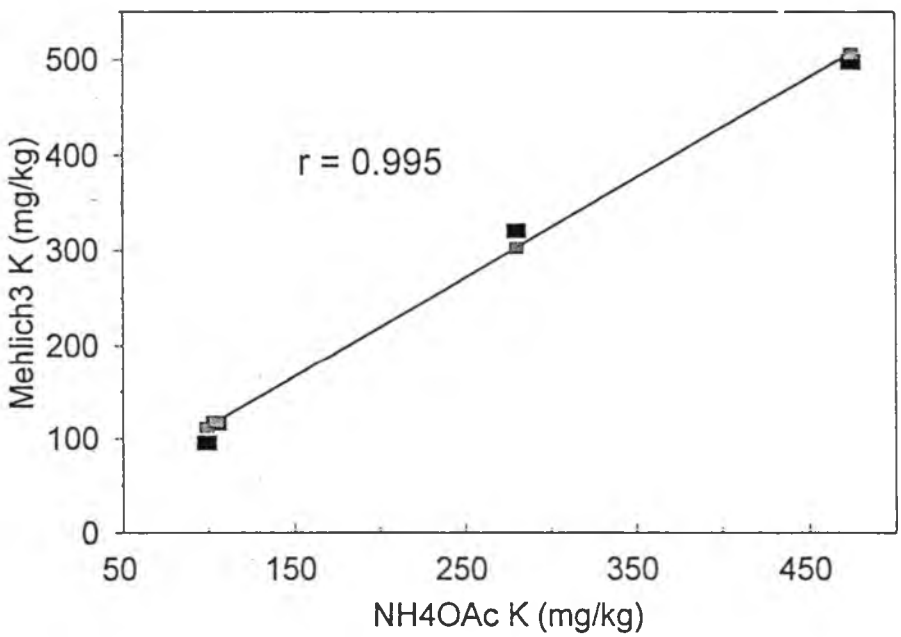

Fig. 97. Correlation between NH4OAc K and Mehlich3 K in an Andisol after a One-Week Incubation.

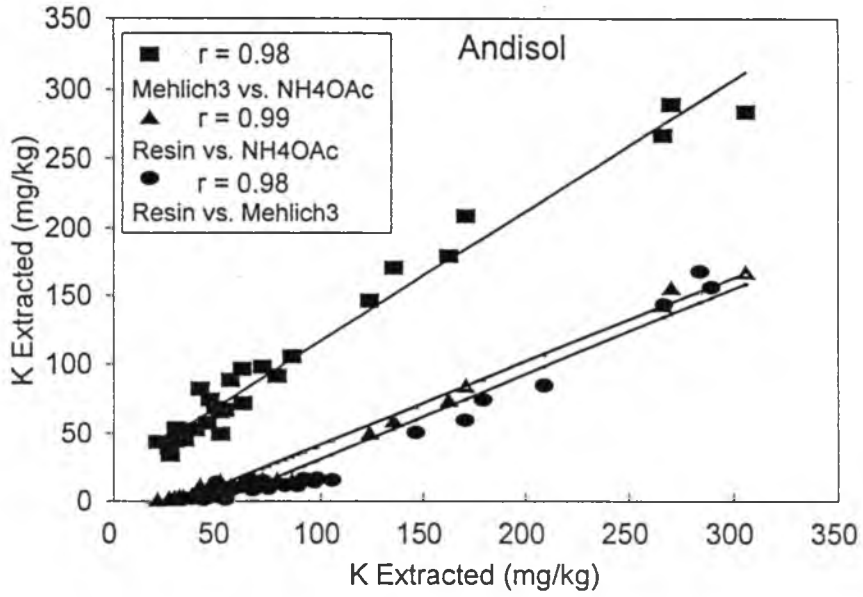

Fig. 98. Correlations between K Extracted by Three Methods after a One-Month Sweet Corn Trial in an Andisol. (Resin K values were multiplied by 20).

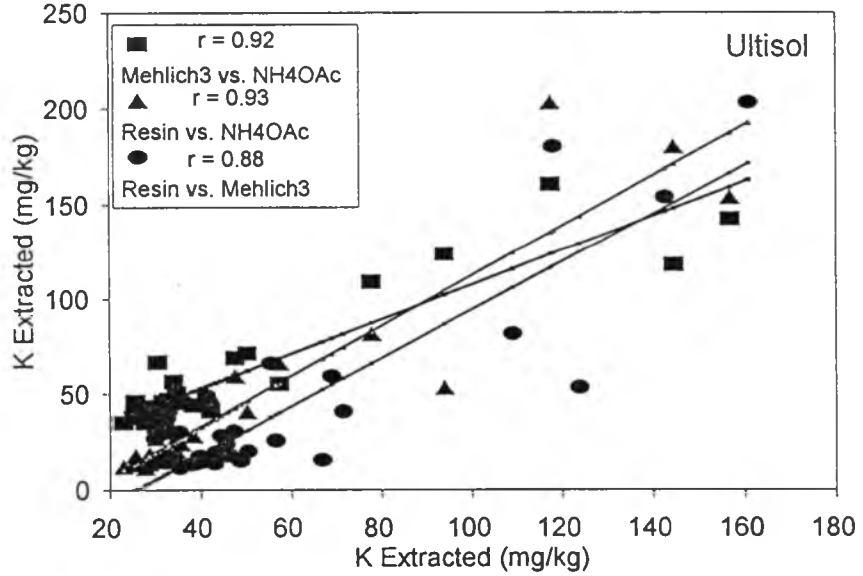

Fig. 99. Correlations between K Extracted by Three Methods after a One-Month Sweet Corn Trial in an Ultisol. (Resin K values were multiplied by 60).

The use of air-dried samples after the trial in the Ultisol and the P effect on K extracted may have contributed to these lower r values. There were also highly linear correlations between changes in NH_4OAc K, Mehlich3 K, and Resin K during the one-month trials from the Ultisol and in NH_4OAc K and Mehlich3 K from the Andisol (Figs. 100 and 101).

The sensitivity of K test values to soil K levels and C.V.'s for sampling: The sensitivity of K extraction methods was indicated only by sensitivity coefficient B because the data could not be fit using the linear plateau model. Mehlich3 K and NH_4OAc K were very similar in sensitivity to K applied in both soils, while Resin K was much less sensitive (Table 15). The similar sensitivity coefficient B values obtained by Mehlich3 K and NH_4OAc K were not unexpected because both of these extractants contain NH_4^+. The sampling error C.V. from Resin K was highest and that from Mehlich3 was lowest in the Ultisol, while in the Andisol Mehlich3's C.V. was higher than the C.V.'s for Resin and NH_4OAc, which were nearly equal.

RELATIONSHIPS BETWEEN MEHLICH3 K AND PLANT PARAMETERS IN CHINESE CABBAGE TRIALS

The performance of Mehlich3 as a K extractant was also tested in Chinese cabbage trials on both soils. The relationships between Mehlich3 K and Chinese cabbage dry matter production in both soils were very similar to those between K applied and dry matter yield (Figs. 102 and 103).

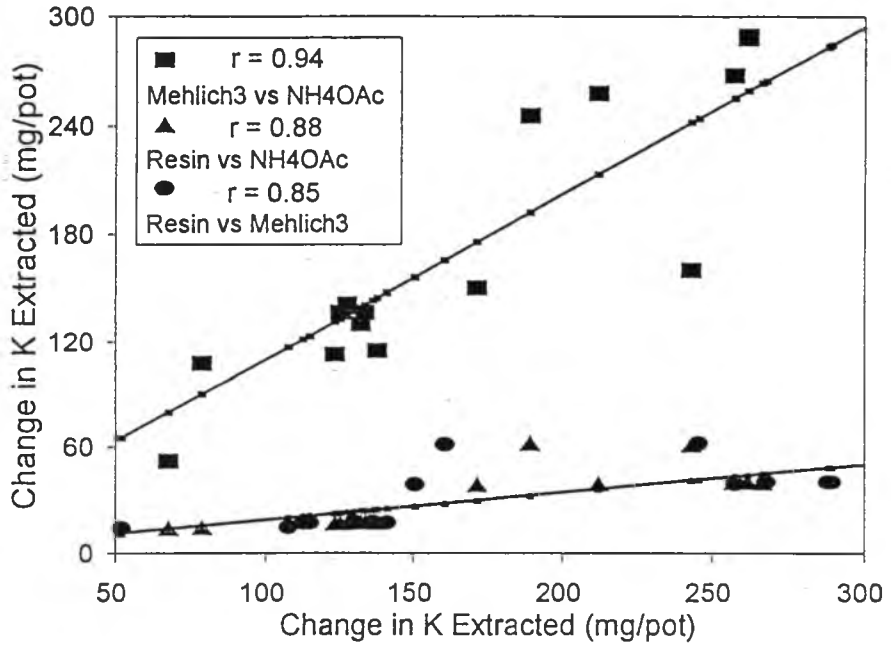

Fig. 100. Correlations between the Change in NH4OAc, Mehlich3, and Resin Extractable K during a One-Month Sweet Corn Trial in an Ultisol .

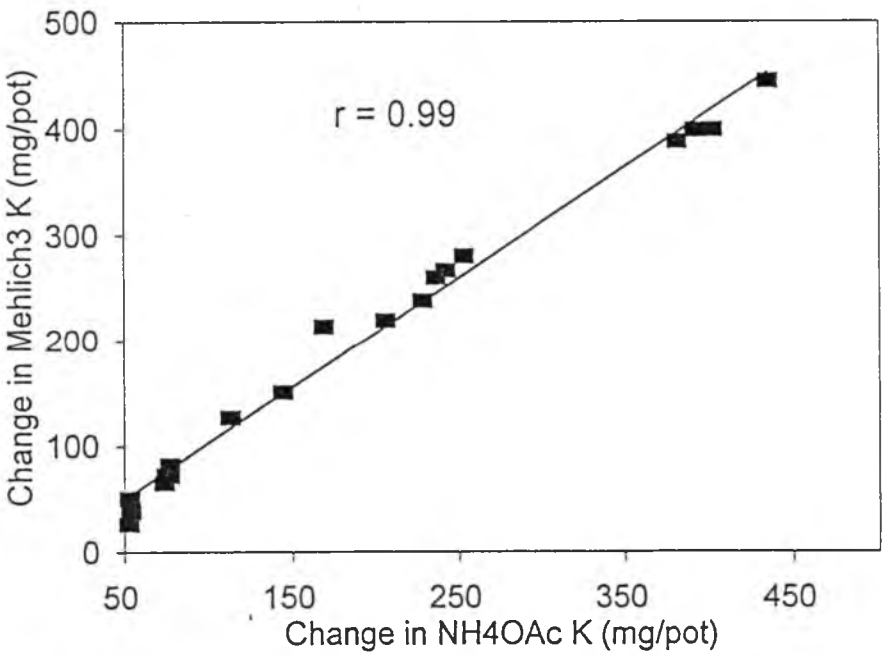

Fig. 101. Correlation between the Change in NH4OAc K and the Change in Mehlich3 K during a One-Month Sweet Corn Trial in an Andisol.

Table 15. Sensitivity Coefficient and Coefficient of Variation (%) for Sampling of K Extraction Methods

Coefficients	------- K extraction method ------		
	NH_4OAc	Mehlich3	Resin
	Sweet corn in the Ultisol		
Sensitivity Coef. B†	0.57	0.54	0.09
C.V. (%)	12.02	10.50	14.44
	Sweet corn in the Andisol		
Sensitivity Coef. B	1.43	1.49	-
C.V. (%)	7.61	12.07	7.72

† The ratio of K extracted to K applied.

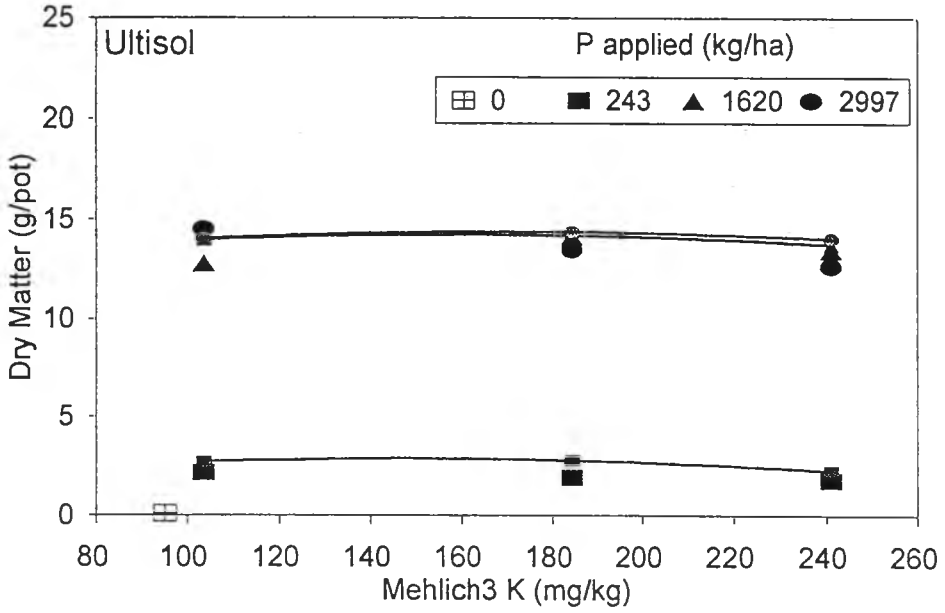

Fig.102. Response of Chinese Cabbage Dry Matter Yield to Mehlich3 K Extracted from an Ultisol after a One-Week Incubation.

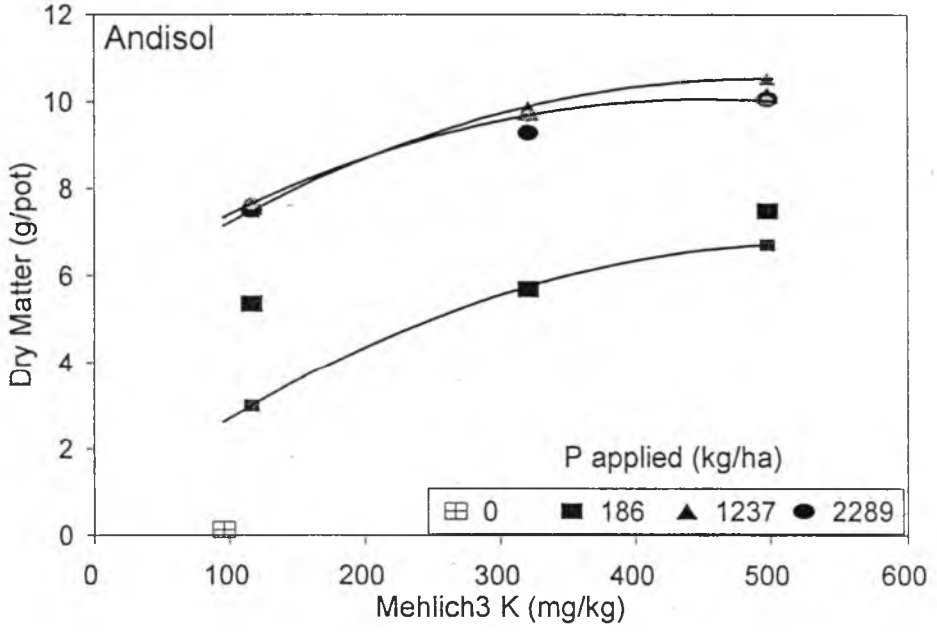

Fig. 103. Response of Chinese Cabbage Dry Matter Yield to Mehlich3 K Extracted after a One-Week Incubation in an Andisol.

Tissue K was linearly related to Mehlich3 K at all P levels in the Ultisol. However, much less of the total variability was explained by the linear relationship at the lowest P application rate than at the two higher rates (Fig. 104). The low r^2 value at the lowest P application rate might have been caused by the small plant samples that were available for analysis at this P level. There were linear relationships between K uptake and Mehlich3 K at higher P levels in the Ultisol. No such relationship was found at the lowest P application level (Fig. 105). The small plant samples and the poor response of dry matter production to K levels at this P level, both of which resulted from the strong P limitation, may account for the poor relationship. The relations for Mehlich3 K with tissue K and K uptake were much better in the Andisol than in the Ultisol (Fig. 106). This result is similar to that obtained in the sweet corn trials. The uptake of K was also closely related to the change in Mehlich3 K in both soils, with r^2 values of 0.85 and 0.98 for the Ultisol and Andisol, respectively (Fig. 107).

PERCENTAGES OF K RECOVERED BY NH_4OAC AND MEHLICH3 AFTER INCUBATION

The percentage of added K that was recovered by these extraction methods from incubation soil samples was calculated using the following equation:

$$K_{rec}\ (\%) = 100 * (K_{fin} - K_{cont}) / K_{added},$$

where $K_{rec}\ (\%)$ is the percentage of K recovered after the one-

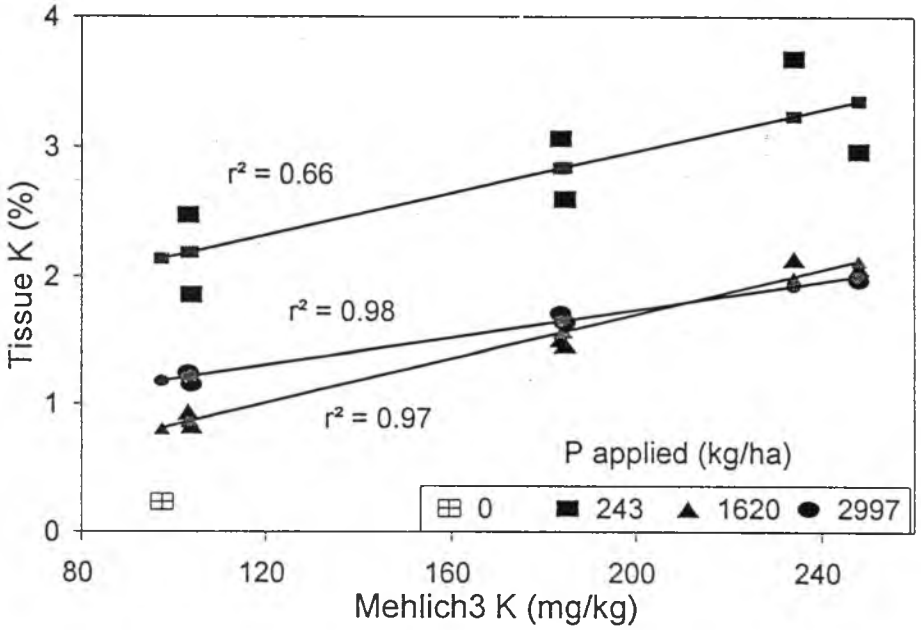

Fig. 104. Relationship between Chinese Cabbage Tissue K Concentration and Mehlich3 K Extracted from an Ultisol after a One-Week Incubation.

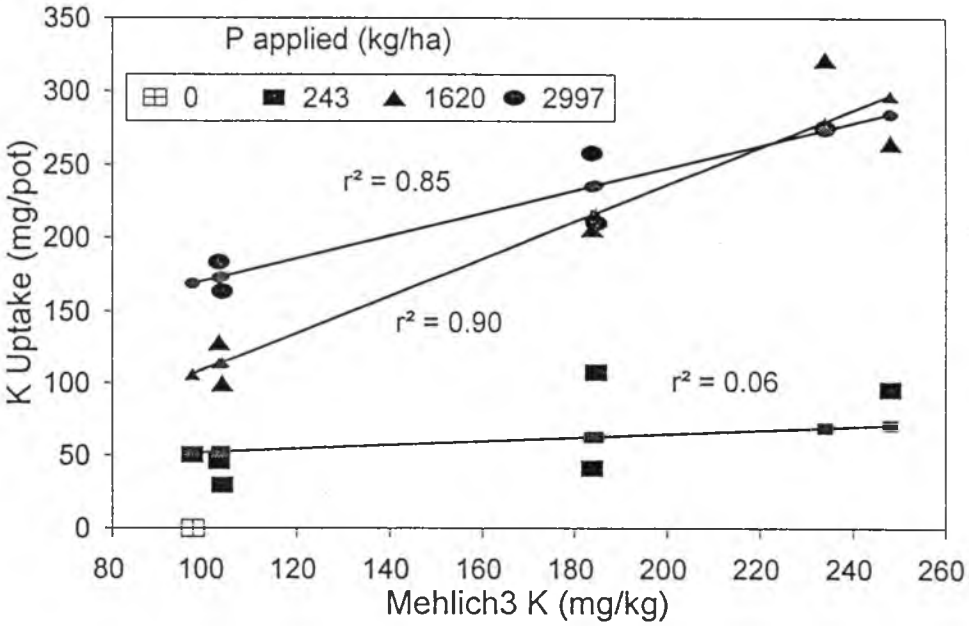

Fig. 105. Relationship between Chinese Cabbage K Uptake and Mehlich3 K Extracted from an Ultisol after a One-Week Incubation.

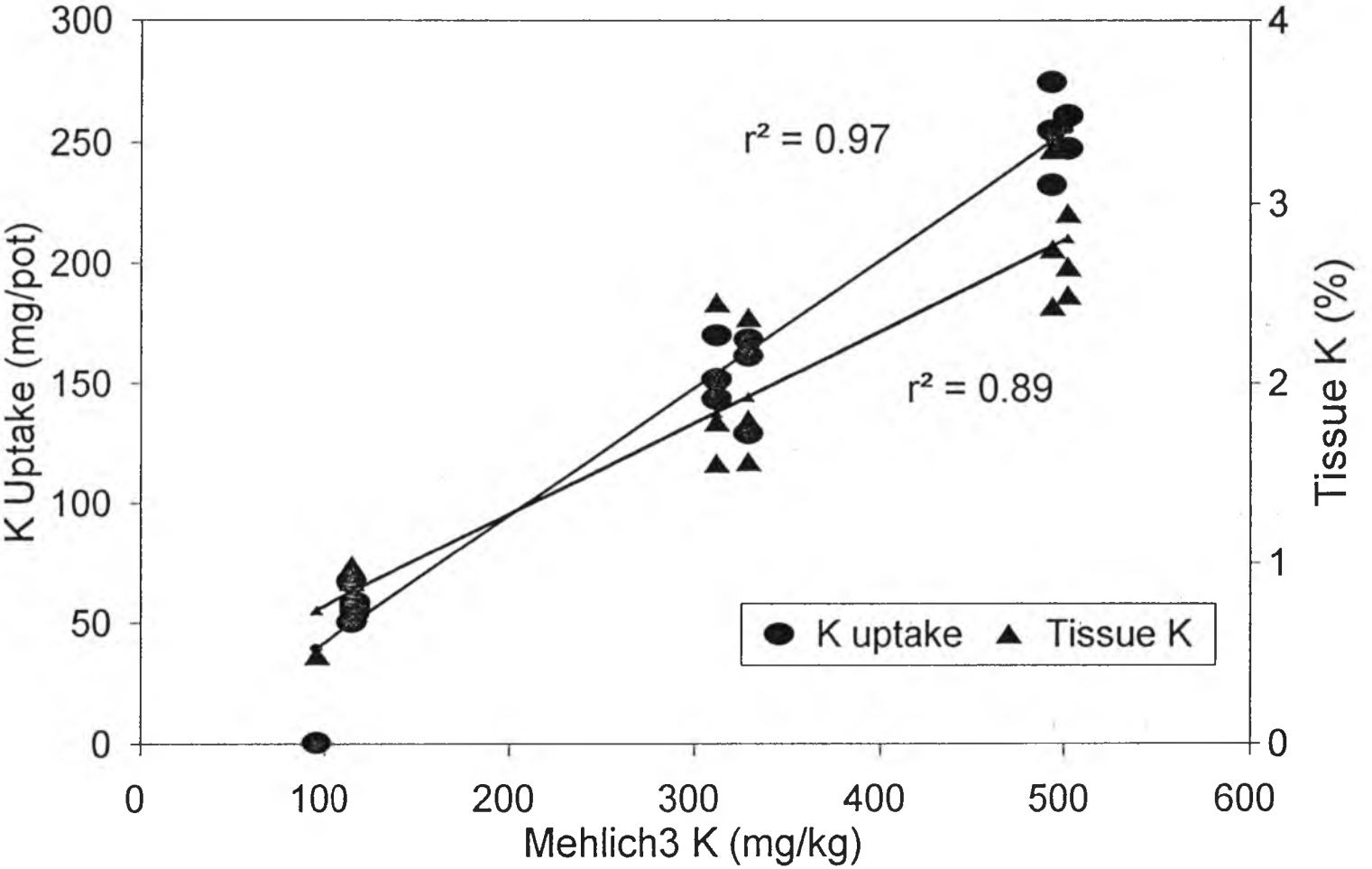

Fig. 106. Relations of Mehlich3 K Extracted after a One-Week Incubation with K Uptake and Tissue K Concentration of Chinese Cabbage in an Andisol.

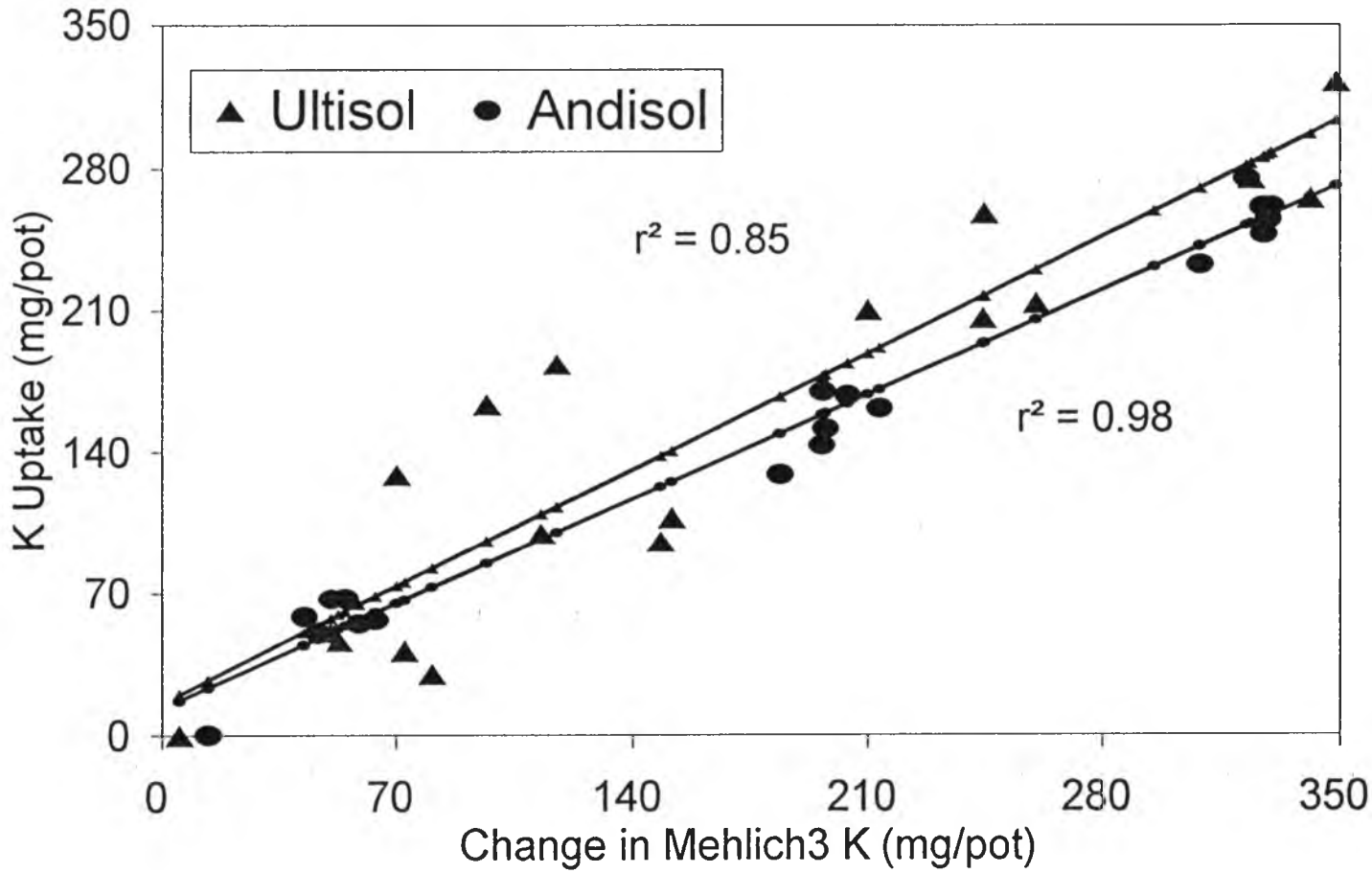

Fig. 107. Relationship between K Uptake and the Change in Mehlich3 K during a One-Month Chinese Cabbage Trial in Two Soils.

week incubation, K_{fin} is the amount of K extracted after one-week incubation from the samples to which K had been applied, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, and K_{added} is the K applied, with all terms expressed in units of mg K/pot.

In the Ultisol, recovery of added K by NH_4OAc after the one-week incubation was about 100% (Table 16). This agrees with results in the literature (McLean and Watson, 1985). Recovery by Mehlich3 was also close to 100% at the two higher K levels, but was significantly lower at the lowest K level (Table 16). These results suggest that a small amount of added K may be sorbed in this soil at sites that are not accessible to a single extraction with Mehlich3.

In the Andisol, the percentages of K recovered by NH_4OAc and Mehlich3 were close to 100% at the two higher K levels, but were significantly lower at the lowest level for both extractants. In this case, the percentage was only about 20% for recovery by NH_4OAc while it was about 70% for recovery by Mehlich3 (Table 16). Based on the results from many previous studies, Sticher (1972) concluded that K is preferentially adsorbed by allophane. The decrease in K fixation with increased K application may result from the existence of adsorption sites on the surfaces of particles containing allophane or other amorphous materials, which react specifically with K^+ via mechanisms that have yet to be determined. However, our results indicate that when a small

Table 16. K Recovery† by NH4OAc and Mehlich3 in Two Soils after a One-Week Incubation.

K applied mg/pot	NH4OAc K mg/pot	K recovery %	Mehlich3 K mg/pot	K recovery %
		Ultisol		
0	163.11	-	190.14	-
25	189.34	104.92 a‡	207.16	68.08 b
167	327.05	98.17 a	368.81	106.99 a
308	478.47	102.39 a	482.13	94.80 a
		Andisol		
0	98.98	-	95.90	-
30	104.59	18.70 b	116.61	69.03 b
200	280.25	90.64 a	320.56	112.33 a
370	474.69	101.54 a	497.99	108.67 a

† K recovery was calculated as $100\% * (K_{fin}-K_{cont}) / K_{added}$, where K_{fin} is the amount of K extracted from the samples to which K had been applied, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, and K_{added} is the K applied.

‡ For each soil, means in the same column followed by the same letter are not significantly different (based on $LSD_{.05}$ comparisons).

amount of K was applied to this soil, most of the K was sorbed tightly enough so that it could not be released by a single extraction with NH_4OAc.

K 'lost' during one-month trials: The difference between K extracted after incubation and K extracted after the one-month trials generally did not equal measured plant K uptake. The magnitude of this discrepancy was estimated for each treatment using the equation

$$K_{lost} = K_{cont} + K_{added} - (K_{up} + K_{fin}),$$

where K_{lost} is the amount of applied K that could not be accounted for by plant uptake and soil extractions, K_{fin} is the amount of K extracted from a sample taken after the trial, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, K_{added} is the K applied, and K_{up} is the K content of the above-ground portions of the plants, with all terms expressed in units of mg K/pot. Thus K_{lost} is the portion of extractable K (plus any K added) that was in the soil at planting but that was neither taken up by the plant tops nor recovered by extraction after the one-month trial.

In all trials, K_{lost} tended to increase with K application rate. Both positive and negative values were observed, but the positive values were predominant (Tables 17-20). The negative K_{lost} values suggest a release of K during the cropping period from sites that retain K when exposed to a single application of these extractants. Four potential

Table 17. Amounts of Initial Soil K (Native Extractable K + K Added) in the Ultisol that were not Recovered by Soil K Extraction or Plant Uptake Measurements following a One-Month Sweet Corn Trial.†

P added kg/ha	K added mg/pot	Tissue K %	K uptake mg/pot	AAK mg/pot	K lost mg/pot	M3K mg/pot	K lost mg/pot
0‡	0	2.65	38.25	98.69	26.17	126.22	25.66
0§	0	2.57	41.42	93.30	40.42	121.17	24.44
Means	0	2.61	39.84	96.00	33.29	123.70	25.05
112	25	3.27	106.13	64.52	16.95	85.86	26.38
747	25	0.70	97.97	53.07	37.07	82.98	34.19
1382	25	0.66	125.31	55.04	7.76	71.38	18.45
Means	25	1.54	109.80	57.54	20.60	80.07	26.34
112	167	4.00	137.67	152.86	39.58	192.32	27.15
747	167	0.94	156.09	58.69	115.33	72.13	128.91
1382	167	1.04	190.60	70.33	69.19	89.79	76.75
Means	167	1.99	161.45	93.96	74.70	118.08	77.60
112	308	4.33	133.22	279.27	58.74	281.13	83.90
747	308	1.71	298.98	66.01	106.23	103.82	95.45
1382	308	1.44	297.52	64.97	108.73	99.19	101.53
Means	308	2.49	243.24	136.75	91.24	161.38	93.63

† NH_4OAc K (AAK) and Mehlich3 K (M3K) values are the amounts of K extracted after the one-month trials. K lost is the amount of K that could not be accounted for by plant uptake and K extracted and was calculated as $K_{cont} + K_{added} - (K_{up} + K_{fin})$, where K_{fin} is the amount of K extracted from a sample taken after the trial, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, K_{added} is the K applied, and K_{up} is the K content of the above-ground portions of the plants.

‡ Complete control treatment.

§ Partail control treatment.

Table 18. Amounts of Initial Soil K (Native Extractable K + K Added) in the Andisol that were not Recovered by Soil K Extraction or Plant Uptake Measurements following a One-Month Sweet Corn Trial.†

P added kg/ha	K added mg/pot	Tissue K %	K uptake mg/pot	AAK mg/pot	K lost mg/pot	M3K mg/pot	K lost mg/pot
0‡	0	2.607	51.26	48.95	-1.23	64.31	-19.67
0§	0	1.970	39.07	48.77	11.14	58.50	-1.68
Means	0	2.288	45.17	48.86	4.95	61.41	-10.68
84	30	2.527	69.47	51.75	7.76	81.90	-25.47
563	30	1.577	90.69	30.35	7.94	48.95	-13.75
1041	30	0.937	96.22	27.74	5.02	41.06	-11.38
Means	30	1.680	85.46	36.61	6.90	57.30	-16.87
84	200	3.633	88.77	156.64	53.57	186.33	20.80
563	200	2.823	195.42	46.93	56.62	72.28	28.19
1041	200	1.667	220.22	37.98	40.78	53.12	22.56
Means	200	2.708	168.14	80.52	50.32	103.91	23.85
84	370	4.410	113.06	280.98	74.94	280.18	72.66
563	370	3.590	283.29	86.18	99.51	105.62	76.99
1041	370	2.857	323.19	68.31	77.48	83.56	59.15
Means	370	3.619	239.85	145.16	83.97	156.45	69.60

† NH_4OAc K (AAK) and Mehlich3 K (M3K) values are the amounts of K extracted after the one-month trials. K lost is the amount of K that could not be accounted for by plant uptake and K extracted and was calculated as $K_{cont} + K_{added} - (K_{up} + K_{fin})$, where K_{fin} is the amount of K extracted from a sample taken after the trial, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, K_{added} is the K applied, and K_{up} is the K content of the above-ground portions of the plant.

‡ Complete control treatment.

§ Partail control treatment.

Table 19. Amounts of Initial Soil K (Native Extractable K + K Added) in the Ultisol that were not Recovered by Mehlich3 (M3) or Plant Uptake Measurements following a One-Month Chinese Cabbage Trial. †

P added kg/ha	K added mg/pot	Tissue K %	K uptake mg/pot	M3K mg/pot	K lost mg/pot
0‡	0	0.31	0.31	182.44	12.70
0§	0	0.24	0.24	187.05	0.24
Means	0	0.28	0.28	184.74	6.47
243	25	2.27	49.39	157.17	10.15
1620	25	0.91	119.17	122.31	-26.35
2997	25	1.22	177.02	96.06	-57.94
Means	25	1.47	115.20	125.18	-24.72
243	167	2.76	55.75	264.61	36.78
1620	167	1.49	211.48	114.18	31.48
2997	167	1.67	226.25	147.31	-16.42
Means	167	1.97	164.49	175.36	17.28
243	308	3.21	59.61	388.89	49.64
1620	308	2.10	284.30	142.92	70.92
2997	308	1.11	145.79	181.96	170.39
Means	308	2.14	163.23	237.92	96.98

† Mehlich3 K (M3K) values are the amounts of K extracted after the one-month trials. K lost is the amount of K that could not be accounted for by plant uptake or soil K extraction and was calculated as $K_{cont} + K_{added} - (K_{up} + K_{fin})$, where K_{fin} is the amount of K extracted from a sample taken after the trial, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, K_{added} is the K applied, and K_{up} is the K content of the above-ground portions of the plant.

‡ Complete control treatment.

§ Partial control treatment.

Table 20. Amounts of Initial Soil K (Native Extractable K + K Added) in the Andisol that were not Recovered by Mehlich3 (M3) or Plant Uptake Measurements following a One-Month Chinese Cabbage Trial.†

P added kg/ha	K added mg/pot	Tissue K %	K uptake mg/pot	M3K mg/pot	K Lost mg/pot
0‡	0	0.74	1.48	58.43	12.09
0§	0	0.49	0.65	55.58	17.30
Means	0	0.62	1.07	57.01	14.70
186	21	0.96	51.95	31.87	5.56
1237	21	0.82	63.98	24.60	0.81
2289	21	0.83	64.39	34.75	-9.76
Means	21	0.87	60.11	30.41	-1.13
186	140	2.41	136.74	41.09	32.25
1237	140	1.68	167.27	23.22	19.59
2289	140	1.68	160.04	28.12	21.93
Means	140	1.92	154.68	30.81	24.59
186	259	3.13	237.70	37.31	55.78
1237	259	2.62	270.48	27.51	32.80
2289	259	2.54	259.07	26.71	45.01
Means	259	2.76	255.75	30.51	44.53

† Mehlich3 K (M3K) values are the amounts of K extracted after the one-month trials. K lost is the amount of K that could not be accounted for by plant uptake or soil K extraction and was calculated as $K_{cont} + K_{added} - (K_{up} + K_{fin})$, where K_{fin} is the amount of K extracted from a sample taken after the trial, K_{cont} is the amount of K extracted immediately after incubation from samples that received no K application, K_{added} is the K applied, and K_{up} is the K content of the above-ground portions of the plant.

‡ Complete control treatment.

§ Partial control treatment.

explanations (besides experimental error) might be offered for the positive K_{lost} values: 1) root K was not included in our measurements of plant K uptake; 2) readily exchangeable K could have been converted to a less accessible form; 3) a small amount of K could have been leached from the pots (although leaching of K is not very likely for these soils with pH adjusted to 6); and 4) additioned CEC from applied P held K against K extractors.

Although highly weathered soils are not commonly expected to fix K, K fixation by allophane is well documented (Malavolta, 1985; Sticher, 1972). Some workers have also reported K fixation in other tropical soils (Malavolta, 1985). K fixation in the Ultisol (Haiku series), Oxisol (Molokai series), and Andisol (Pane and Kula series) soil orders has also been reported by Duque (1988). In his study, the Andisol generally fixed more K than either the Oxisol or the Ultisol in unfertilized treatments, and the total amount of K fixed was highest in the Andisol.

In our study, average K_{lost} values were highest in the Ultisol for the sweet corn trial and for the highest K rate in the Chinese cabbage trial. Comparisons between soils in our study, however, are complicated by the effects of the plants and of the P applications. Plant uptake in general would be expected to increase K release, but the net effect of K uptake on K_{lost} would also depend on the extent of immobilization of K in the root tissue. Unfortunately, the

relationships between K uptake, root K content, and the observed variation in K_{lost} could not be assessed with the available data. The relationship between soils and K fixation cannot be determined from the K_{lost} data because we are unable to isolate the effects of the other potential contributors to K_{lost}.

SELECTION OF K EXTRACTION METHODS

Mehlich3 performed as well as NH_4OAc in both soils for the crop tested in terms of the coefficients of determination for regressions of K uptake and K applied with K extracted, and in terms of the sensitivity of K test values to soil K levels and the C.V. for sampling (Table 15). In the Ultisol for sweet corn, Mehlich3 K was better related than Resin K to K uptake and K applied (Table 21). In both soils, however, Resin K was as well correlated with NH_4OAc K as was Mehlich3 K (Table 21). Nonetheless, in terms of the sensitivity of K test values and the C.V. for sampling, Resin usually did not perform as well as the other methods.

Estimation of Critical Levels

CRITICAL EXTRACTABLE P LEVELS

The critical extractable P levels for all extraction methods tested in each trial are shown in Table 22. For the sweet corn in the Ultisol, the critical levels as estimated by the linear plateau model (Cox, 1992) were very close to those estimated by the quadratic model for all four methods. (Critical levels for the quadratic model were estimated at

Table 21. Summary of r Values for the Correlations between K Extraction Methods.

Results Prior to Planting (incubation study)

	NH_4OAc	Mehlich3
	Ultisol	
Mehlich3	0.99**†	-
Resin	0.99**	0.99**
	Andisol	
Mehlich3	0.99**	-

Results after completion of trials

	NH_4OAc	Mehlich3
	Ultisol	
Mehlich3	0.92**	-
Resin	0.93**	0.88**
	Andisol	
Mehlich3	0.98**	-
Resin	0.99**	0.98**

† Highly significant (α = 0.01).

Table 22. P Critical Levels (in mg/kg) Estimated by a Quadratic Model and by a Linear Plateau Model.

Soil	Model	Mod.Truog	Mehlich3	Olsen	Resin
		Sweet corn			
Ultisol	Quadratic	125	97	49	2.33
	Linear plateau	142	100	51	2.14
Andisol	Quadratic	≥ 163	≥ 65	≥ 73	≥ 1.87
		Chinese cabbage			
Ultisol	Quadratic	286	150	-	-
	Linear plateau	174	102	-	-
Andisol	Quadratic	115	50	-	-
	Linear plateau	135	43	-	-

85% of maximum predicted dry matter yield in this study, rather than at 90 or 95%, to compensate for the higher P requirements of young crops.) Both of these models fit the data very well in this trial and produced similar r^2 values for the relation between P extracted and relative dry matter production. The data for the sweet corn trial in the Andisol did not permit an estimation of a critical level because dry matter production was still increasing approximately linearly with P application rate up to the highest P level tested (Figs. 36-39). However, the critical P level was estimated to be greater or equal to the P level at 85% of maximum dry matter yield by a quadratic model. For the Chinese cabbage trial in Ultisol, the estimates from the linear plateau model were much lower than those from the quadratic model (Table 22). In this trial, the linear plateau model fit the data better than the quadratic model as indicted by higher R^2 values from the linear plateau model. The differences between the estimated critical levels (Table 22) in the Chinese cabbage trial in the Ultisol may have been caused by too few observations in a range near the critical level to permit a precise estimation. Nevertheless, the linear plateau models did fit the data better for that trial, especially at the extractable P levels nearest to the critical range, and thus they also can be expected to provide better estimates of the corresponding critical levels. In the trial on the Andisol, the linear plateau model also fit

the data some better than did the quadratic model. However, the critical levels as estimated by the linear plateau model were very close to those estimated by the quadratic model for both Modified Truog and Mehlich3 P in the Andisol (Table 22).

CRITICAL EXTRACTABLE K LEVELS

In the Ultisol, there was little response in dry matter production to K applied or to K extracted by either sweet corn or Chinese cabbage (Figs. 73, 74, 77, and 98). For sweet corn, there might have been some response to the K applications at the two highest P levels, but the results are not consistent enough for any critical level above the native soil K level to be suggested. For Chinese cabbage, no response to K was indicated even at the highest P level. Thus the critical K levels for young Chinese cabbage were estimated to be less than or equal to the extractable K levels for the lowest K application rate. These extractable K levels were 95, 103, and 9 mg/kg for NH_4OAc, Mehlich3, and Resin, respectively.

Treatment means from the trials in the Andisol indicate a response to K applied at all but the lowest soil P level. The critical extractable K levels for young sweet corn and Chinese cabbage were estimated at the highest P level using the quadratic model. The critical NH_4OAc and Mehlich3 K levels in the Andisol (for 85% of maximum predicted dry matter yield) were estimated approximately to be 186 and 200 mg/kg, respectively, for young sweet corn. The critical

Mehlich3 K level for young Chinese cabbage was estimated to be 218 mg/kg.

CHAPTER 5

SUMMARY AND CONCLUSIONS

A series of four pot experiments was conducted in a greenhouse to assess the suitability of Mehlich3 and Resin extractants for extraction of soil P and K from two Hawaii soils. The study also included Modified Truog and Olsen extractants for extraction of P and the NH_4OAc extractant for extraction of K as standards for comparison with the two new methods. Two soils, an Ultisol (Leilehua series---a clayey, oxidic, isothermic Typic Kandihumult) and an Andisol (Maile series---a hydrous, isomesic Acrudoxic Hydrudand), and two crops, sweet corn and Chinese cabbage, were used in this study. The four P extraction methods and three K extraction methods were compared over a wide range of soil P (0-2997 kg/ha) and K (0-278 kg/ha) application levels.

Applications of P greatly increased dry matter yield, P and K uptake, and tissue P in both sweet corn and Chinese cabbage on both the Ultisol and the Andisol. Applications of K resulted in small inconsistent increases in dry matter yield of sweet corn in the Ultisol. Chinese cabbage did not respond to K application in this soil. Applications of K increased dry matter yield of both crops in the Andisol, except at the lowest P application level. The increases in sweet corn dry matter yield were not statistically significant, however. Applications of P caused a marked decrease of tissue K concentration in both soils.

In terms of coefficients of determination for the regression between plant parameters (dry matter production, P uptake, and tissue P) and P extracted, Mehlich3 performed as well as the Modified Truog and Olsen extraction methods over a wide range of P levels in both soils, for both crops. In terms of the accuracy of diagnoses, the sensitivity of P test values, and C.V. for sampling, Mehlich3 P usually ranked between Olsen P and Modified Truog P.

In terms of coefficients of determination for the regression between K uptake, and K applied with K extracted, and in terms of sensitivity of K test values and C.V. for sampling, Mehlich3 K performed as well as NH_4OAc K in both soils for the crop tested. The highly significant linear correlations between the Mehlich3 P, Modified Truog P, and Olsen P methods and between Mehlich3 K and NH_4OAc K suggest that it would be practical, for these soil-crop combinations, to switch from the conventional procedures, with separate extractions for P and K, to simultaneous P and K extraction with Mehlich3. Use of a simple linear regression model would allow for a rough conversion between results obtained from a Mehlich3 extraction and those obtained from Modified Truog P, Olsen P, and NH_4OAc K extractions if this was desired for the soils studied. Mehlich3's more soil dependent nature in terms of C.V. and sensitivity to P applied imply that more soils need to be tested in order to have better assessment of Mehlich3's performance in highly weathered soils. However,

its rather consistent sensitivity coefficient A values across soils and crops suggest that Mehlich3 P could be a very promising index of soil P availability.

In both soils, Resin P was as well related to dry matter production, P uptake, and P applied as were the other three methods, but it was less well correlated than Mehlich3 P was with Modified Truog P and Olsen P. In the Ultisol for sweet corn, Mehlich3 K was better related than Resin K to K uptake and K applied. In both soils, however, Resin K was as well correlated with NH_4OAc K as was Mehlich3 K. Nonetheless, in terms of the accuracy of diagnoses, the sensitivity of P and K test values, and C.V. for sampling, Resin was usually poorer than other methods. And also, there are probably three other major disadvantages of the Resin extraction method: 1) very low P concentrations in soil extracts from the Resin method make use of colorimetric methods impossible for soil samples with low P levels; 2) the long extraction time (three days of incubation) and greater number of steps required in the Resin extraction procedure compared to Mehlich3 extraction; and 3) a large amount of soil sample (50 g) is required. These shortcomings could limit the adoption of this method for routine analysis. Consequently, while both Mehlich3 and Resin offer the important advantage of a simultaneous extraction of P and K, Mehlich3 seems the better choice.

Appendix A. Effect of P and K Applications on Plant Parameters and on Modified Truog (M.T.) P, Mehlich3 (M3) P, Olsen P, and Resin P Extracted after a One-Month Sweet Corn Trial on an Ultisol.

P added kg/ha	K added kg/ha	DM g/pot	Height cm	Tissue P %	P uptake mg/pot	M.T. P mg/kg	M3 P mg/kg	Olsen P mg/kg	Resin P mg/kg
0 #	0	1.43	37	0.08	1.10	4.23	1.59	2.56	0.10
0 §	0	1.57	38	0.07	1.12	4.45	1.61	2.45	0.19
0	150	1.50	36	0.16	2.64	3.84	1.55	2.47	-
112	23	3.37	53	0.10	3.25	18.44	9.34	6.95	0.15
112	150	3.43	51	0.10	3.33	17.17	13.00	7.36	0.12
112	278	3.07	50	0.10	3.18	16.89	9.36	7.27	0.20
448	90	10.83	83	0.14	15.56	66.29	46.83	23.54	-
448	210	11.40	81	0.14	16.45	64.39	49.40	24.60	-
747	0	14.00	92	0.18	25.03	113.49	90.28	43.46	-
747	23	13.97	89	0.19	26.09	128.30	80.06	42.89	1.66
747	150	17.07	94	0.16	27.75	146.67	81.98	46.07	2.07
747	278	17.90	97	0.18	31.80	127.57	75.80	41.67	2.04
1046	90	18.77	101	0.22	41.95	166.45	142.19	68.26	-
1046	210	20.80	100	0.24	50.17	148.12	142.21	70.07	-
1382	23	18.87	100	0.28	53.43	226.05	193.29	79.27	4.30
1382	150	18.33	96	0.26	47.70	235.39	154.56	91.91	4.36
1382	278	20.90	100	0.25	52.20	218.94	174.15	79.65	4.38

Complete control.
§ Partial control.

Appendix B. Effect of P and K Applications on Tissue K and K Uptake and on NH4OAc (AA) K, Mehlich3 (M3) K, and Resin K Extracted after a One-Month Sweet Corn Trial on an Ultisol.

P added kg/ha	K added kg/ha	Tissue K %	K uptake mg/pot	AA K mg/kg	M3 K mg/kg	Resin K mg/kg
0 #	0	2.65	38.25	49.35	63.11	0.39
0 §	0	2.57	41.42	46.65	60.59	0.62
112	23	3.27	106.13	32.26	42.93	0.33
747	23	0.70	97.97	26.54	41.49	0.18
1382	23	0.66	125.31	27.52	35.69	0.18
448	90	1.73	185.68	-	-	-
1046	90	0.94	176.75	-	-	-
112	150	4.00	137.67	76.43	96.16	0.84
747	150	0.94	156.09	29.35	36.07	0.23
1382	150	1.04	190.60	35.17	44.90	0.28
448	210	2.47	277.90	-	-	-
1046	210	1.04	217.09	-	-	-
112	278	4.33	133.22	139.63	140.56	2.24
747	278	1.71	298.98	33.00	51.91	0.25
1382	278	1.44	297.52	32.48	49.60	0.25

Complete control.
§ Partial control.

Appendix C. Effect of P and K Applications on Plant Parameters and on Modified Truog (M.T.) P, Mehlich3 (M3) P, Olsen P, and Resin P Extracted after a One-Month Sweet Corn Trial on an Andisol.

P added kg/ha	K added kg/ha	DM g/pot	Height cm	Tissue P %	P uptake mg/pot	M.T. P mg/kg	M3 P mg/kg	Olsen P mg/kg	Resin P mg/kg
0 #	0	1.97	34	0.040	0.79	17.51	8.19	5.44	0.24
0 §	0	2.00	38	0.050	1.00	15.93	7.35	5.62	0.15
84	23	2.73	41	0.053	1.44	23.77	14.67	10.60	0.17
84	150	2.43	42	0.050	1.22	25.30	13.26	10.26	0.23
84	278	2.57	43	0.053	1.38	23.03	13.30	10.17	0.16
337	90	4.03	58	0.067	2.69	53.92	24.00	25.47	-
337	210	5.27	63	0.080	4.21	55.03	24.65	25.47	-
563	23	5.87	70	0.090	5.28	80.66	37.91	38.47	0.74
563	150	7.23	74	0.087	6.19	83.84	35.30	38.22	0.54
563	278	8.07	79	0.103	8.40	78.25	35.36	36.70	0.80
788	90	8.93	79	0.093	8.43	113.60	47.48	52.01	-
788	210	10.73	85	0.097	10.33	115.06	46.30	51.59	-
1041	23	10.27	85	0.113	11.63	153.01	57.97	71.56	1.59
1041	150	13.53	91	0.113	15.45	159.59	60.59	67.88	1.89
1041	278	12.07	88	0.127	15.11	152.92	59.10	68.42	1.52

Complete control.
§ Partial control.

Appendix D. Effect of P and K Applications on Tissue K and K Uptake and on NH4OAc (AA) K, Mehlich3 (M3) K, and Resin K Extracted after a One-Month Sweet Corn Trial on an Andisol.

P added kg/ha	K added kg/ha	Tissue K %	K uptake mg/pot	M3 K mg/kg	AA K mg/kg	Resin mg/kg
0 #	0	2.607	51.26	64.31	48.95	0.57
0 §	0	1.970	39.07	58.50	48.77	0.61
84	23	2.527	69.47	81.90	51.75	0.70
563	23	1.577	90.69	48.95	30.35	0.15
1041	23	0.937	96.22	41.06	27.74	0.11
337	90	3.340	134.69	-	-	-
788	90	1.837	154.81	-	-	-
84	150	3.633	88.77	186.33	156.64	3.66
563	150	2.823	195.42	72.28	46.93	0.45
1041	150	1.667	220.22	53.12	37.98	0.25
337	210	3.867	195.75	-	-	-
788	210	2.417	257.16	-	-	-
84	278	4.410	113.06	280.18	280.98	7.80
563	278	3.590	283.29	105.62	86.18	1.39
1041	278	2.857	323.19	83.56	68.31	0.63

Complete control.
§ Partial control.

Appendix E. Effect of P and K Applications on Plant Parameters and on Modified Truog (M.T.) P, Mehlich3 (M3) P, and Mehlich3 K Extracted after a One-Month Chinese Cabbage Trial on an Ultisol.

P added kg/ha	K added kg/ha	DM g/pot	Lf lth# cm	Tissue P %	P uptake mg/pot	Tissue K %	K uptake mg/pot	M.T. P mg/kg	M3 P mg/kg	M3 K mg/kg
0 §	0	0.10	1	0.070	0.07	0.31	0.31	4.28	0.93	91.22
0 ¶	0	0.10	2	0.070	0.07	0.24	0.24	4.66	1.13	93.53
243	23	2.20	9	0.160	3.46	2.27	49.39	35.09	18.19	78.58
243	150	1.93	8	0.140	2.71	2.76	55.75	34.87	17.62	132.30
243	278	1.80	8	0.157	2.79	3.21	59.61	36.92	17.55	194.44
972	210	11.60	19	0.300	35.06	1.67	198.09	156.27	94.84	-
1620	23	12.80	13	0.470	61.69	0.91	119.17	326.62	209.66	61.16
1620	150	14.17	19	0.400	56.78	1.49	211.48	322.95	208.35	57.09
1620	278	13.50	19	0.403	54.35	2.10	284.30	375.12	220.02	71.46
2268	210	11.00	17	0.420	46.48	1.74	191.40	493.14	274.42	-
2997	23	14.50	20	0.507	73.52	1.22	177.02	629.66	345.65	48.03
2997	150	13.50	19	0.453	61.25	1.67	226.25	602.24	342.23	73.65
2997	278	12.70	19	0.467	59.11	1.11	145.79	634.94	353.70	90.98

Leaf length.
§ Complete control.
¶ Partial control.

Appendix F. Effect of P and K Applications on Plant Parameters and on Modified Truog (M.T.) P, Mehlich3 (M3) P, and Mehlich3 K Extracted after a One-Month Chinese Cabbage Trial on an Andisol.

P added kg/ha	K added kg/ha	DM g/pot	Lf lth# cm	Tissue P %	P uptake mg/pot	Tissue K %	K uptake mg/pot	M.T. P mg/kg	M3 P mg/kg	M3 K mg/kg
0 §	0	0.20	3	0.060	0.18	0.74	1.48	13.24	6.81	82.30
0 ¶	0	0.13	3	0.060	0.06	0.49	0.65	13.10	7.15	78.28
186	23	5.37	17	0.200	10.73	0.96	51.95	32.35	10.32	44.89
186	150	5.70	18	0.193	10.99	2.41	136.74	28.75	7.40	57.88
186	278	7.50	19	0.200	14.82	3.13	237.70	31.92	9.60	52.55
742	90	8.33	22	0.420	35.02	1.24	105.05	110.44	36.31	-
742	210	9.60	22	0.393	37.63	2.15	206.92	111.10	34.61	-
1237	23	7.60	21	0.520	39.52	0.82	63.98	209.08	70.80	34.65
1237	150	9.77	23	0.540	52.53	1.68	167.27	221.82	71.48	32.71
1237	278	10.17	23	0.473	48.10	2.62	270.48	204.73	67.94	38.74
1732	90	9.17	23	0.573	52.30	1.17	108.87	319.32	106.83	-
1732	210	9.97	22	0.540	53.65	1.96	200.76	311.18	118.81	-
2289	23	7.53	21	0.693	52.16	0.83	64.39	472.55	193.73	48.95
2289	150	9.30	23	0.620	58.93	1.68	160.04	417.36	145.86	39.60
2289	278	10.07	22	0.587	58.91	2.54	259.07	447.22	141.65	37.62

Leaf length.
§ Complete control.
¶ Partial control.

APPENDIX G

Regression Equations for Dry Matter Yield Responses to P and K Applied.

Soil	Equation	R^2
	Sweet corn	
Ultisol	$Y = 0.93+0.0266(P)-0.000011(P)^2+0.0022(K)-0.000014(K)^2+0.000013(P*K)$	0.97
Andisol	$Y = 1.72+0.006(P)+0.0000019(P)^2+0.0099(K)-0.000036(K)^2+0.000011(P*K)$	0.83
	Chinese cabbage	
Ultisol	$Y = 0.0126(P)-0.0000026(P)^2-0.0018(K)+0.0000061(K)^2-0.0000018(P*K)$	0.91
Andisol	$Y = 1.126+0.0073(P)-0.0000021(P)^2+0.0337(K)-0.000055(K)^2+0.000004(P*K)$	0.92

Regression Equations for Tissue P and P Uptake Responses to P Applied.

Soil	Equation	r^2 or R^2
	Sweet corn	
Ultisol	Tissue P = 0.092+0.00012(P)	0.70
	P uptake = 0.27+0.0381(P)	0.93
Andisol	Tissue P = 0.049+0.000068(P)	0.91
	P uptake = 0.026+0.0135(P)	0.83
	Chinese cabbage	
Ultisol	Tissue P = 0.078+0.00029(P)-(5.4E-08)$(P)^2$	0.96
	P uptake = -5.616+0.0518(P)-0.0000096$(P)^2$	0.92
Andisol	Tissue P = 0.115+0.0004(P)-(8.7E-08)$(P)^2$	0.91
	P uptake = 3.315+0.0494(P)-0.000012$(P)^2$	0.95

Regression Equations for Relationships of Dry Matter Yield with Extractable P and K Applied.§

Soil	Equation	R^2
	Sweet corn	
Ultisol	$Y = 0.568+0.1746(MTP)-0.00045(MTP)^2+0.0029(K)-0.000011(K)^2+0.000071(MTP*K)$	0.96
	$Y = 0.746+0.2213(M3P)-0.0007(M3P)^2+0.00175(K)+0.000013(K)^2-0.000043(M3P*K)$	0.97
	$Y = 0.746+0.483(OlP)-0.0033(OlP)^2+0.0052(K)-0.000019(K)^2+0.000195(OlP*K)$	0.98
	$Y = 0.746+9.5416(RsP)-1.1492(RsP)^2+0.0140(K)-0.000024(K)^2-0.00095(RsP*K)$	0.96
	Sweet corn	
Andisol	$Y = 0.568+0.0476(MTP)+0.000084MTP^2+0.0076(K)-0.000029(K)^2+0.00005(MTP*K)$	0.89
	$Y = 0.524+0.1379(M3P)+0.00031M3P^2+0.0062(K)-0.00003(K)^2+0.00023(M3P*K)$	0.80
	$Y = 1.199+0.0938(OlP)+0.00044(OlP)^2+0.0102(K)-0.000041(K)^2+0.00022(OlP*K)$	0.84
	$Y = 1.035+6.1526(OlP)-0.4588(RsP)^2+0.0150(K)-0.000045(K)^2+0.0052(RsP*K)$	0.82
	Chinese cabbage	
Ultisol	$Y = -0.188+0.0594(MTP)-0.000058(MTP)^2+0.0111(K)-0.000021(K)^2-0.00002(MTP*K)$	0.90
	$Y = -0.0098+0.0994(M3P)-0.00017M3P^2+0.0105(K)-0.00002(K)^2-0.000028(M3P*K)$	0.91
	Chinese cabbage	
Andisol	$Y = 0.986+0.0356(MTP)-0.000049(MTP)^2+0.0409(K)-0.000074(K)^2-0.000027(MTP*K)$	0.89
	$Y = 0.749+0.11(M3P)-0.0004(M3P)^2+0.044(K)-0.000075(K)^2-0.00013(M3P*K)$	0.88

§ MTP--Modified Truog P; M3P-- Mehlich3 P; OlP--Olsen P; RsP--Resin P.

Regression Equations for Relationships of Extractable P with Tissue P and P uptake.§

Soil	Equation	r^2 or R^2
Ultisol	Tissue P = 0.096+0.00073(MTP)	0.66
	Tissue P = 0.097+0.00097(M3P)	0.71
	Tissue P = 0.094+0.0020(OlP)	0.68
	Tissue P = 0.079 + 0.0717(RsP) -0.00697$(RsP)^2$	0.87
	P uptake = 1.202+0.2245(MTP)	0.87
	P uptake = 1.669+0.2993(M3P)	0.93
	P uptake = 0.687+0.6111(OlP)	0.91
	P uptake = -0.703+21.4891(RsP)-2.2142$(RsP)^2$	0.93
Andisol	Tissue P = 0.044+0.0005(MTP)	0.86
	Tissue P = 0.038+0.0015(M3P)	0.88
	Tissue P = 0.044+0.0011(OlP)	0.88
	Tissue P = 0.033+0.11(RsP)-0.0339$(RsP)^2$	0.93
	P uptake = -1.365+0.1021(MTP)	0.90
	P uptake = -2.152+0.2718(M3P)	0.82
	P uptake = -1.054+0.2214(OlP)	0.84
	P uptake = 0.023+8.9249(RsP)	0.85
	Chinese cabbage	
Ultisol	Tissue P = 0.097+0.0013(MTP)-0.0000012$(MTP)^2$	0.94
	Tissue P = 0.103+0.0022(M3P)-0.0000031$(M3P)^2$	0.96
	P uptake = -2.560+0.2399(MTP)-0.000044$(MTP)^2$	0.92
	P uptake = -2.120+0.4095(M3P)-0.00064$(M3P)^2$	0.93
Andisol	Tissue P = 0.123-0.0000028(MTP)+0.00027$(MTP)^2$	0.90
	Tissue P = 0.150-0.00587(M3P)+0.000017$(M3P)^2$	0.89
	P uptake = 4.287+0.2784(MTP)-0.00037$(MTP)^2$	0.93
	P uptake = 6.058+0.758(m3P)-0.0027$(M3P)^2$	0.92

§ MTP--Modified Truog P; M3P-- Mehlich3 P; OlP--Olsen P; Rsp--Resin P.

Regression Equations for Relationships of K Extracted with Tissue K and with K Uptake.§

P added kg/ha	Equation	r^2	Equation	r^2
		Sweet corn in the Ultisol		
112	Tissue K= 2.624 + 0.0076 (AAK)	0.88	K uptake = 84.724 + 0.2895 (AAK)	0.51
747	Tissue K= 0.016 + 0.0065(AAK)	0.44	K uptake = -28.921+ 1.2396 (AAK)	0.65
1382	Tissue K= 0.014 + 0.00647 (AAK)	0.85	K uptake = -15.137 + 1.3564 (AAK)	0.85
112	Tissue K= 2.486 + 0.0079 (M3K)	0.87	K uptake = 77.818 + 0.3114 (M3K)	0.54
747	Tissue K= -0.174 + 0.0072 (M3K)	0.50	K uptake = -58.373+ 0.4544 (M3K)	0.68
1382	Tissue K= -0.052 + 0.0065 (M3K)	0.78	K uptake = -27.994 + 1.3482 (M3K)	0.77
112	Tissue K= 2.973 + 0.0435 (RsK)	0.82	K uptake = 97.983 + 1.6563 (RsK)	0.48
747	Tissue K= 0.193 + 0.0429 (RsK)	0.56	K uptake = 12.112 + 7.8418 (RsK)	0.74
1382	Tissue K= 0.302 + 0.0374 (RsK)	0.82	K uptake = 43.734 + 7.9148 (RsK)	0.83
		Sweet corn in the Andisol		
84	Tissue K = 2.069 + 0.00512(AAK)	0.90	K uptake = 51.726 + 0.1391(AAK)	0.80
563	Tissue K = 0.978 + 0.00538 (AAK)	0.79	K uptake = 38.644 + 0.5323(AAK)	0.97
1041	Tissue K = 0.409 + 0.00458 (AAK)	0.73	K uptake = 31.501 + 0.6430(AAK)	0.98
84	Tissue K = 1.982 + 0.00499 (M3K)	0.90	K uptake = 50.561 + 0.1316(M3K)	0.76
563	Tissue K = 0.932 + 0.0051 (M3K)	0.75	K uptake = 28.432 + 0.5220(M3K)	0.99
1041	Tissue K = 0.334 + 0.00445 (M3K)	0.73	K uptake = 21.251 + 0.6238(M3K)	0.98
		Chinese Cabbage in the Ultisol		
243	Tissue K = 1.355 + 0.00806(M3K)	0.66	K uptake = 39.151 + 0.1295(M3K)	0.06
1620	Tissue K = -0.040 + 0.00874(M3K)	0.97	K uptake = -17.641 + 1.2691(M3K)	0.90
2997	Tissue K = 0.590 + 0.5904(M3K)	0.98	K uptake = 101.106 + 0.7103(M3K)	0.85
		Chinese Cabbage in the Andisol		
	Tissue K = 0.253 + 0.00508(M3K)	0.89	K uptake = -11.621 + 0.5318(M3K)	0.97

§ AAK--NH4OAc K; M3K--Mehlich3 K; RsK--Resin K.

Regression Equations for Relationships between P Extraction Methods.§

Soil	Equation	r^2
	Sweet corn	
Ultisol	M3P = -0.603+0.7395(MTP)	0.91
	M3P = -1.570+1.9964(OIP)	0.93
	OIP = 1.456+0.3608(MTP)	0.93
	RsP = -0.165+0.0187(MTP)	0.84
	RsP = 0.049+0.0239(M3P)	0.79
	RsP = -0.197+0.0533(OIP)	0.88
Andisol	M3P = 4.944+0.3572(MTP)	0.96
	M3P = 4.910+0.7951(OIP)	0.97
	OIP = 0.091+0.0086(MTP)	0.98
	RsP = -0.067+0.0108(MTP)	0.92
	RsP = -0.181+0.0292(M3P)	0.88
	RsP = -0.048+0.0235(OIP)	0.90
	Chinese cabbage	
Ultisol	M3P = 4.177+0.561(MTP)	0.98
Andisol	M3P = 2.071+0.3602(MTP)	0.96

§ MTP--Modified Truog P; M3P-- Mehlich3 P; OIP--Olsen P; RsP--Resin P.

Regression Equations for Relationships between P Extracted and P Applied .§

Soil	Equation	r^2
	Sweet corn	
Ultisol	Mod. Truog P = 1.311+0.1611(P)	0.96
	Mehlich3 P = -3.383+0.1252(P)	0.97
	Olsen P = 0.461+0.0605(P)	0.96
	Resin P = -0.132+0.00313(P)	0.85
Andisol	Mod. Truog P = 11.897+0.1330(P)	0.98
	Mehlich3 P = 8.707+0.0485(P)	0.98
	Olsen P = 4.912+0.0607(P)	0.99
	Resin P = 0.066+0.0014(P)	0.90
	Chinese cabbage	
Ultisol	Mod. Truog P = -9.903+0.2124(P)	0.98
	Mehlich3 P = -2.568+0.1120(P)	0.98
Andisol	Mod. Truog P = -8.808+0.1913(P)	0.96
	Mehlich3 P = -5.156+0.0688(P)	0.92

§ MTP--Modified Truog P; M3P-- Mehlich3 P; OlP--Olsen P; RsP--Resin P.

Regression Equations for Relationships between K Extraction Methods before Sweet Corn Trials and between them after Trials.§

Soil	Equation	r^2	Equation	r^2
		Before trial		After trial
Ultisol	M3K = 18.644 + 0.949 (AAK)	0.98	M3K = 16.409 + 0.9098 (AAK)	0.85
	RsK = -5.899 + 0.1632(AAK)	0.98	RsK = -0.248 + 0.0165 (AAK)	0.87
	RsK = -8.857 + 0.1704(M3K)	0.99	RsK = -0.409 + 0.01586 (M3K)	0.78
Andisol	M3K = 8.721 + 1.0479(AAK)	0.99	M3K = 21.880 + 0.9486 (AAK)	0.97
			RsK = -0.957 + 0.0303 (AAK)	0.98
			RsK = -1.565 + 0.0310 (M3K)	0.96

§ AAK--NH4OAc K; M3K--Mehlich3 K; RsK--Resin K.

Regression Equations for Relationships between K Extracted and K Applied.§

Equation	r^2	Equation	r^2
	Ultisol		Andisol
AAK = 81.0748 + 0.5647 (K)	0.997	AAK = 72.797 + 1.4313(K)	0.995
M3K = 95.189 + 0.5396(K)	0.989	M3K = 88.219 + 1.4895(K)	0.997
RsK = 7.282 + 0.0926(K)	0.991		

§ AAK--NH4OAc K; M3K--Mehlich3 K; RsK--Resin K.

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