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THE UNIVERSITY OF ALBERTA

INORGANIC AND EXTRACTABLE PHOSPHORUS OF SOME SOLONETZIC SOILS

OF ALBERTA

by

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A THESIS

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The undersigned certify that they have read, and recommend to the
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ABSTRACT

Even though a summary of Agricultural Soil and Feed Testing Laboratory's data indicated fairly high levels (20 - 25 ppm) of $NH_4F + H_2SO_4$ extractable P in a Solonetzic area, it was not certain that the high levels were due to Solonetzic soils. This investigation was begun with the following goals: to determine if the higher levels of extractable P in a Solonetzic area are definitely associated with Solonetzic soils; to account for the higher levels; and to ascertain the importance of the higher levels of extractable P to barley growth in a greenhouse experiment.

Solonetzic and Chernozemic Ap samples, along with samples from virgin profiles of Solonetzes, Solods, and their geographically associated Chernozemic and Luvisolic series were taken from the southern and central regions of Alberta. Soil pH, oxalate extractable Al and Fe, organic C, particle-size distribution, inorganic P forms (by a modified Chang and Jackson procedure), organic P, and total P were determined. Extractable P of the Ap samples was measured by $NH_4F + H_2SO_4$, $NaHCO_3$, Ca-lactate + HCl, and EDTA methods. Finally, barley was grown on Ap samples to determine its response to applied P.

All four methods released more extractable P from the Solonetzic than from the Chernozemic Ap samples, though the Ca-lactate + HCl and EDTA extractable P values did not show a clear difference between the two groups. Comparison of the Soil and Feed Testing Laboratory's data with the soils of the Tofield-Ryley area showed generally higher levels of $NH_4F + H_2SO_4$ extractable P in the Solonetzic than in the Chernozemic soils.

Fractionation results indicated the preponderance of Al-P and Fe-P in the Solonetzic and Ca-P in the Chernozemic sola and Ap samples. Ca-P was the preponderant form in all the C horizons. Organic and total P contents were higher in the Solonetzic than in the Chernozemic Ah horizons; however, in the Ap samples this trend for organic P was not apparent. Occluded-P contents tended to be high in the sola compared to the C horizons.

The higher levels of extractable P of the Solonetzic Ap samples could not be explained by P fertilizer applications, total P content of the parent material, nor by contents of clay and organic P. The high acidity in the upper sola of Solonetzic soils, indicative of intense weathering conditions, apparently has resulted in relatively high contents of oxalate extractable Al and Fe and these probably account for the higher levels of Al-P and Fe-P and lower levels of Ca-P in the Solonetzic than in the Chernozemic sola. Since close correlations were obtained between the levels of Al- and Fe-P and extractable P measured by the four methods, the higher levels of extractable P in the Solonetzic than in the Chernozemic Ap samples can be explained by the higher contents of Al-P and Fe-P in the former.

In the greenhouse, average dry matter yields of the check pots were not different for the Solonetzic and Chernozemic Ap samples and there were significant increases in barley yields with P applications in both groups. Whereas the NH_4F + H_2SO_4 and $NaHCO_3$ methods separated Solonetzic and Chernozemic Orders in their extractable P levels, a clear-cut difference did not exist between these Orders in their plant-available P status.

ACKNOWLEDGMENTS

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I. INTRODUCTION

Alberta has a large proportion of the Solonetzic soils in Western Canada.
In spite of the considerable research done on their physical, chemical,
mineralogical, and agronomic properties, little information is available
on the phosphorus status of these soils. Since they occupy approximately
four million hectares of agricultural land in Alberta and since phosphorus
is the fertilizer nutrient added in second largest quantities in Alberta,
it is important to study the phosphorus status of Solonetzic soils.

In earlier investigations reported in the literature, attention was
focused on total phosphorus in the determination of phosphorus supplying
power of soils. However, total phosphorus analyses failed to predict
phosphorus availability to plants. Further researches led to the idea of
extracting a readily soluble portion of soil phosphorus. Thus, many
workers used dilute solutions of acids, bases, and salts to relate the
amount of extractable phosphorus ("available phosphorus") in soils to
plant growth.

Among the various reagents to measure extractable phosphorus in soils,
two which have received much attention in Western Canada during the last
two decades are 0.03 M NH_4F + 0.015 M H_2SO_4 and 0.5 M $NaHCO_3$. In an
investigation on 79 surface samples (0 - 15 cm) of Dark Brown, Thin Black,
Degraded Black, and Gray Wooded soils of Alberta, Robertson (1962) studied
the suitability of NH_4F + H_2SO_4 and $NaHCO_3$ extractants. He found close
correlation between the levels of extractable phosphorus measured by both

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reagents and barley growth in the greenhouse. Although there were about

10 Solonetzic samples in the study, no test was done to examine the

suitability of the two methods for soils of widely different physical

and chemical properties, as in the case of Solonetzic and Chernozemic

soils. For practical reasons he recommended the $NH_4F + H_2SO_4$ reagent,

which was in use at the Agricultural Soil and Feed Testing Laboratory

(ASFTL), to measure extractable phosphorus of Alberta soils.

A summary (Cameron and Toogood, 1970) of the ASFTL's data, on 63,000

farmer-supplied samples from 1962 to 1969, revealed some trends in the

distribution of $NH_4F + H_2SO_4$ extractable phosphorus. The extractable

phosphorus levels increased gradually from 10 - 15 ppm in the southeast

corner of Alberta to 26 - 35 ppm in the Edmonton area and beyond. An

island of fairly high values (20 - 25 ppm) to the southeast of Edmonton

was reported and it corresponds approximately to the main area of

Solonetzic soils in Alberta. Though the predominant soils in this island

are Solonetzic, it is not certain from the data that the higher levels of

extractable phosphorus are due to Solonetzic soils. Moreover, very little

information is available elsewhere on the extractable phosphorus status

of Solonetzic soils.

Therefore, this investigation was begun with the following goals:

to find if the higher levels of $NH_4F + H_2SO_4$ extractable phosphorus

in a Solonetzic area are definitely associated with Solonetzic

soils;

to seek an explanation, through physical and chemical properties,

for the levels of $NH_4F + H_2SO_4$ extractable phosphorus in

Solonetzic soils; and

to ascertain the importance of the levels of $NH_4F + H_2SO_4$

extractable phosphorus in Solonetzic soils to barley growth in

a greenhouse experiment.

II. REVIEW OF LITERATURE

A. SOLONETZIC SOILS OF ALBERTA

Alberta has about four million hectares of Solonetzic soils and the
majority of these occur in a relatively level area of shallow ground
--- moraine extending about 480 km from Vegreville to Taber. Smaller areas
exist in the Wetaskiwin - Edmonton - Westlock region, the Peace River
region, and in a region south of the Cypress Hills (Bowser, Milne, and
Cairns, 1962b and Odynsky, 1945).

Solonetzic soils of Alberta owe their origin to an accumulation of
soluble salts in portions of the landscape. The salt accumulation is
usually from groundwater and the salts are generally sodium and magnesium
sulphates. As long as groundwater brings salts to the surface continuously,
there is little pedogenic development beyond the stage of Saline Regosols.
However, any factor that decreases or intercepts groundwater flow inhibits
the continuous upward movement of salts in the discharge area and
ultimately decreases salt concentration at the soil surface. Once ground-
water ceases to concentrate salts at the soil surface, precipitation
leaches the salts into the soil and an entirely new process begins
(Pawluk and Dumanski, 1969).

The leaching causes desalinization and when the salt content is below
0.10 - 0.15%, the exchangeable sodium peptizes the colloids (Bentley and
Rost, 1947) which move downward and concentrate in the B layer. This
layer is the solonetzic B horizon (Bnt) and it is characteristic of the

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Solonetzic Order of soils as defined in the System of Soil Classification

for Canada (Canada Department of Agriculture, 1970). Morphologically,

the Bnt has columnar or prismatic macrostructure that can be broken into

blocky mesostructure. The blocks are hard to very hard in consistence and

have dark surface stains. Chemically, the Bnt has a ratio of exchangeable

calcium to sodium of 10 or less. In this regard, some have reported high

percentages of exchangeable magnesium in the B horizons of profiles which

show typical solonetzic features (Ehrlich and Smith, 1958; Ellis and

Caldwell, 1935; Riecken, 1943; and Rost and Maehl, 1943). However,

Bowser et al. (1962b) noted considerable overlap in the percentages

of exchangeable magnesium found in soils of the Solonetzic and Chernozemic

Orders.

As leaching continues, hydrogen ions gradually replace exchangeable

sodium and the A horizon becomes more acidic. Simultaneously, there is

a structural breakdown of the Bnt horizon.

There have been several studies on the Solonetzic soils of Alberta:

chemical and mineralogical characterization (Arshad and Pawluk, 1966);

general characterization (Bowser et al., 1962b); study on the evolution

of profile development (Brunelle, 1969); determination of equilibrium

ion ratios (Khan and Webster, 1966); and base exchange studies (Wynnyk,

1950). In spite of this extensive research, little information is

available on the phosphorus status of these soils.

B. INORGANIC PHOSPHORUS FORMS OF SOILS

1. Fractionation of Inorganic Phosphorus of Soils

Though there have been several fractionation procedures for soil

phosphorus (Chang and Jackson, 1957; Dean, 1938; Fisher and Thomas, 1935; Fraps, 1906; Ghani, 1943; Saunders, 1959; Williams, 1950; and Williams, 1937), the Chang and Jackson procedure, or modifications of it, (Glenn et al., 1959*; Peterson and Corey, 1966; Syers, Smillie, and Williams, 1972; and Williams, Syers, and Walker, 1967) has received much attention. According to the Chang and Jackson procedure, six forms of inorganic phosphorus are obtained by treating the soil successively with the following reagents:

a. 1 M NH_4Cl -- water soluble plus loosely bound;

b. 0.5 M NH_4F (pH 7.0) -- aluminum-bound;

c. 0.1 M NaOH -- iron-bound;

d. 0.25 M H_2SO_4 -- calcium-bound;

e. 0.3 M Na-citrate and Na-dithionite -- reductant soluble iron-bound; and

f. 0.5 M NH_4F (pH 7.0) plus 0.1 M NaOH -- occluded aluminum- and iron-bound phosphorus.

Since this procedure was developed from studies on apatite and synthetic phosphates of aluminum and iron, problems arose when it was used for fractionating soil phosphorus, especially that of recently fertilized soils. The main problems were nonselectivity of NH_4F in the separation of aluminum- and iron-bound phosphorus (Fife, 1959-63 and Khin and Leeper, 1960) and resorption of phosphorus by sesquioxides during NH_4Cl, NH_4F, and NaOH extractions (Bromfield, 1967a, 1967b, 1970; Smith, 1965a, 1972; and Williams et al., 1967). A modification of the Chang and Jackson procedure by Glenn et al. (1959) reduced some of the errors due to nonselectivity. The modified procedure is as follows (M. L. Jackson,

* Glenn, R. C., Hsu, P. H., Jackson, M. L., and Corey, R. B. 1959.
  Flow sheet for soil phosphate fractionation. Agron. Abstr. p. 9.

personal communication):

   a. 1 M NH_4Cl;

   b. 0.5 M NH_4F (pH 8.2);

   c. 0.1 M NaOH;

   d. 0.3 M Na-citrate, 1 M $NaHCO_3$, and Na-dithionite;

   e. 0.1 M NaOH; and

   f. 0.25 M H_2SO_4.

The original Chang and Jackson procedure has also been modified by other investigators (Peterson and Corey, 1966; Syers et al., 1972; and Williams et al., 1967). Several researchers have used the Chang and Jackson procedure or a modification of it (Glenn et al., 1959) to fractionate the native inorganic phosphorus of soils (Dahnke, Malcolm, and Menendez, 1964; Halstead, 1967; Juo and Ellis, 1968a; Levesque, 1967; Martens, Lutz, and Jones, 1969; Westin and Buntley, 1967; and Westin and DeBrito, 1969). Some workers have used the modified method of Williams et al. (1967) (Syers et al., 1970 and Williams and Walker, 1969):

   a. 1 M NH_4Cl for 30 min;

   b. 0.5 M NH_4F (pH 8.2) for 24 hr with correction for resorption of phosphate from solution during extraction;

   c. 0.1 M NaOH + 1 M NaCl for 17 hr;

   d. Na-citrate-dithionite-bicarbonate;

   e. 0.5 M HCl for 1 hr, followed by 1 M HCl for 4 hr if first HCl-P is greater than 20 ppm;

   f. ignition at 550C for 1 hr followed by 1 M HCl for 16 hr; and

   g. Na_2CO_3 fusion.

Because of some of the errors inherent in the fractionation procedure, even after resorption corrections, the results obtained have to be interpreted carefully. The NH_4Cl-P consists of soil solution phosphorus and easily soluble phosphate compounds of sodium, potassium, ammonium, calcium, and magnesium. Since the NH_4Cl-P will be resorbed by sesquioxides and calcium carbonate during extraction, the concentration of this fraction reported is usually low for soils. The NH_4F-P (Al-P) form may contain all of the aluminum phosphates plus some of the phosphorus resorbed during NH_4Cl extraction. In the case of NH_4F extraction also, resorption of phosphorus due to oxides of iron and calcium carbonate occurs. Consequently, the NaOH-P (Fe-P) may include all the unoccluded iron phosphates plus the phosphorus resorbed during NH_4F extraction. In calcareous soils, calcium carbonate may resorb some of the phosphorus released during NaOH treatment. Reductant soluble iron-bound phosphorus consists of phosphorus occluded in iron oxides during the process of chemical weathering. Treatment with NaOH, after the sodium citrate-bicarbonate-dithionite extraction for reductant soluble iron-bound phosphorus, releases aluminum-iron-bound occluded phosphorus. Finally, the H_2SO_4-P (Ca-P) includes most of the remaining calcium phosphate compounds (tri- and octacalcium phosphates, apatites, and precipitates on calcium carbonate particles) and the phosphorus resorbed by calcium carbonate during the previous extractions.

2. Distribution of Inorganic Phosphorus Forms of Soils

The results of fractionation studies of different soils consistently show contrasting trends in the distribution of inorganic phosphorus forms.

Several factors such as the activities of various ions (aluminum, iron, and calcium), pH, parent material, intensity of chemical weathering, fertilizer practices, and activity of soil microorganisms are responsible for the different distributions of inorganic phosphorus forms.

The predominant forms in acid soils are Al-P, Fe-P, and occluded phosphorus (Occl-P); whereas alkaline soils contain more Ca-P than other forms. Generally, neutral soils contain varying proportions of all the forms. These distributions would be expected because, above pH 6 - 7 Ca-P is more stable than Al-P and Fe-P; whereas, below pH 6 - 7 Al-P and Fe-P are more stable than Ca-P (Hsu and Jackson, 1960). It is also observed that highly weathered soils are rich in Al-P, Fe-P, and Occl-P and less weathered soils have more Ca-P than other forms (Chang and Jackson, 1958; Smeck and Runge, 1971; Westin and DeBrito, 1969; and Williams and Walker, 1969). However, exceptions to the theory of increase in Al-P, Fe-P, and Occl-P and decrease of Ca-P with profile development have been reported (Alexander and Robertson, 1968 and Syers et al., 1970).

In general, all forms are greatest in the clay separate and lowest in the sand separate. The phosphorus forms in silt and clay are chiefly Al-P and Fe-P, whereas Ca-P is dominant in the sand. The increase of relative abundance of Ca-P with depth in all separates, as observed by Hanley and Murphy (1970) and Juo and Ellis (1968a) can be explained by the primary origin of Ca-P and secondary origin of Al-P and Fe-P.

C.   INORGANIC PHOSPHORUS FORMS AND EXTRACTABLE

PHOSPHORUS OF SOILS

Many researchers have used several approaches to show the importance of various forms to plant removal of phosphorus or plant growth. Some correlated the amounts of these phosphorus forms and the phosphorus extracted by soil test reagents (e.g. 0.03 M NH_4F + 0.015 M H_2SO_4 and 0.5 M $NaHCO_3$). Close correlations have been observed between the amounts of Al-P and extractable phosphorus (Hawkins and Kunze, 1965) and between both Al-P and Fe-P and extractable phosphorus (Alexander and Robertson, 1968). However, other workers found no close correlation (Blanchar and Caldwell, 1964 and Bornemisza and Fassbender, 1970).

Some workers have tried to relate the amounts of various forms to plant yield. Their studies showed that Al-P (Martens et al., 1969 and Payne and Hanna, 1965), Fe-P (Levesque, 1967), Al-P and NH_4Cl-P (Halstead, 1967), Fe-P and NH_4Cl-P (Al-Abbas and Barber, 1964), and both Al-P and Fe-P (Datta and Khera, 1969) were closely correlated with plant yield. However, Susuki, Lawton, and Doll (1963) reported that Ca-P was also a source of phosphorus to barley in addition to Al-P.

Based on isotopic dilution studies to determine the surface activity of various forms, several workers demonstrated the quick isotopic exchange of Al-P and Fe-P compared to Ca-P (Dunbar and Baker, 1965; Machold, 1963; Tandon and Kurtz, 1968; and Weir and Soper, 1962). Some of these studies also showed that surface Al-P and Fe-P contents are greater than those of surface Ca-P, though the total quantity of Ca-P is the greatest. MacKenzie (1962) and Rotini and El-Nennah (1971) showed that Al-P supplied most of

the soil phosphorus to the soil solution. Exchange studies have also demonstrated the amorphous nature of Al-P and Fe-P.

Other investigators observed the distribution of various forms before and after plant growth in soils. Their data demonstrated the significance of Al-P (Smith, 1965b) and Al-P, Fe-P, and Ca-P as sources of phosphorus to the plants (Singh, Martens, and Obenshain, 1966).

Finally, some have grown plants on synthetic sources of Al-P and Fe-P. Their studies indicated that the relative availability of phosphorus from colloidal Al-P and Fe-P was much greater than that from crystalline Al-P and Fe-P (Juo and Ellis, 1968b; Taylor, Gurney, and Lindsay, 1960; and Taylor et al., 1963).

D. INORGANIC AND EXTRACTABLE PHOSPHORUS OF SOLONETZIC SOILS

Based on the distribution of inorganic phosphorus forms of other soils, one would speculate that there would be more Al-P and Fe-P than Ca-P in the sola of Solonetzic soils. The scanty data from the literature seem to support this speculation. Considerable amounts of Fe-P in the sola of Solonetzic soils have been reported by some European workers (Dmitrenko and Shturmova, 1953; Ghobadian, 1967; and Haas, 1964). However, Mikanaev (1968) observed fair amounts of Ca-P, in addition to Al-P and Fe-P in the Solonetzic profiles.

There is also meagre information on the extractable phosphorus status of Solonetzic soils. In three surface horizons of Solonetzic soils of central Alberta, Cairns (1961) reported fairly high levels of

0.001 M H_2SO_4 extractable phosphorus (42, 47, and 67 ppm). In a computer mapping study, Cameron and Toogood (1970) reported an island of fairly high extractable (0.03 M NH_4F + 0.015 M H_2SO_4) phosphorus values (20 - 25 ppm) to the southeast of Edmonton and this island corresponds approximately to the main area of Solonetzic soils in Alberta. Their study involved averaging, on a township basis using a weighted moving average technique, the extractable phosphorus data from 63,000 farmer-supplied samples.

Kvachi and Panov (1969) observed great reserves of elements (presumably including phosphorus) soluble in acids in complex Solonetzes along the Volga River. In this regard, Szabolcs (1971) stated that the extractable phosphorus content of European Solonetz soils varies within a wide range depending mainly on parent material, pH, soil genesis, and other factors. In contrast, low amounts of extractable (0.5 M $NaHCO_3$ and 0.005 M H_2SO_4) phosphorus were reported for some of the Solodic soils of northeastern Queensland (Jones and Crack, 1970).

In summary, though there have been studies on the physical, chemical, mineralogical, and agronomic properties of Solonetzic soils, little information is available on their phosphorus status either in the local or world literature. Therefore, an investigation to study the phosphorus status of Solonetzic soils of Alberta, with special emphasis on extractable phosphorus, seemed desirable.

III. MATERIALS AND METHODS

A. SOIL SAMPLES

1. Ap Horizon Samples from the Tofield-Ryley Area

Although the summary of the soil test data (Cameron and Toogood, 1970)

showed higher levels of extractable ($NH_4F + H_2SO_4$) phosphorus in an area

of predominant Solonetzic soils compared to adjacent areas of predominant

Chernozemic soils, no field sampling had been done to show conclusively

that the higher levels were associated with Solonetzic soils. Therefore,

it was decided to take Ap horizon samples from soils identified in the

field as Solonetzic and Chernozemic. Though the sampling could have been

done in any number of areas where the Solonetzic and Chernozemic soils

are found together, the Tofield-Ryley area was selected because of a

sharp transition from Chernozemic to Solonetzic soils in it, because of

its proximity to Edmonton, and because of plans to conduct field studies

in this area.

To obtain the samples, the Tofield-Ryley area was traversed along

several municipal roads. From place to place, where inspection revealed

a relatively uniform area of either a representative Solonetzic or

Chernozemic soil, a composite Ap horizon sample was taken from an area

of about 20 x 40 m. Seventeen such samples were taken from both Solonetzic

and Chernozemic soils (see Appendix Table A5 for legal locations of the

sampling sites). At the time of sampling, the fertilizer history of each

site was obtained from the farmer. These samples were air-dried, crushed, and passed through a 2-mm sieve.

2. Virgin Soil Profiles

Three virgin profiles each of Hemaruka (Brown Solonetz), Halliday (Brown Solod), Camrose (Black Solonetz), Daysland (Black Solod), Dnister (Gray Solonetz), and Nakamun (Gray Solod) were chosen to study the inorganic phosphorus status of Solonetzic soils. Along with these, their geographically associated orthic Chernozemic and Luvisolic profiles were also chosen. Thus, three profiles each of Maleb (Orthic Brown Chernozem), Beaverhills (Orthic Black Chernozem), and Cooking Lake (Orthic Gray Luvisol) were selected (see Table A6 for the legal locations of the sampling sites). Soil samples were obtained from the major horizons of all the 27 profiles (Table 1) and altogether, there were 114 samples. These samples were air-dried, crushed, and passed through a 2-mm sieve.

3. Ap Horizon Samples for the Greenhouse Experiment

After determining the extractable ($NH_4F + H_2SO_4$) phosphorus levels in the 34 Ap horizon samples, 15 bulk samples, eight Solonetzic and seven Chernozemic, were obtained from some of the sites in the Tofield-Ryley area. These samples were chosen to represent the range of extractable phosphorus found in the 34 samples. Five other bulk samples, two Solonetzic from the Camrose-Stettler area where field work was in progress and three

Table 1   Virgin soil profiles and their horizons sampled

Soil series*	Classification**	Horizons sampled
Maleb, Mb	Orthic Brown	Ah, Bm, Cca, Ck
Hemaruka, Hu	Brown Solonetz	Ah, Ae, Bnt1, Bnt2, Csk
Halliday, Hd	Brown Solod	Ah, Ae, Bnt, Btsk, Csk
Beaverhills, Bh	Orthic Black	Ah, Bm, Ck
Camrose, Cam	Black Solonetz	Ah, Bnt1, Bnt2, Csaca
Daysland, Dl	Black Solod	Ah, Ae, Bnt1, Bnt2, Csak
Cooking Lake, Ck	Orthic Gray Luvisol	Ae, Bt1, Bt2, Ck
Dnister, Dn	Gray Solonetz	Ae, Bnt1, Bnt2, Ck
Nakamun, Nk	Gray Solod	Ae, Bnt1, Bnt2, Csak

 * Three profiles of each series were sampled.

** According to the System of Soil Classification for Canada, Canada
    Department of Agriculture (1970).

Chernozemic collected for a previous investigation (Omanwar, 1970) from

the Edmonton-Lacombe area, were also used (see Table A7 for legal

locations of the sampling sites). The bulk samples were air-dried,

crushed, and passed through a 6.4-mm sieve.

B. EXTRACTABLE PHOSPHORUS DATA FROM THE ASFTL

The previous computer summary of ASFTL data for extractable

phosphorus (Cameron and Toogood, 1970) was done on a township basis

and used a weighted moving average technique to provide values for each

township. Although that technique provided a broad picture of extract-

able phosphorus for Alberta soils, it tended to mask the difference

between Solonetzic and Chernozemic soils in areas where there was a

sharp transition between the two soil orders. Therefore, it was decided

to average, without weighting, the ASFTL data on a section basis and

to compare the values obtained to the soils as shown on the soil map.

The Tofield-Ryley area, bounded by ranges 16 - 20 and townships 49 - 51

inclusive, was chosen for the reasons already stated and because there

is an area of predominant Solonetzic soils in the middle bounded on

either side by areas of predominant Chernozemic soils (Bowser et al.,

1962a). The extractable phosphorus values were averaged for each

section, with five or more samples, and these values were plotted on

an overlay for the soil map.

C. PHYSICAL AND CHEMICAL ANALYSES

1. Soil pH, Oxalate Extractable Aluminum and Iron, Organic Carbon, and Particle-size Analyses

Soil pH was measured in 0.01 M $CaCl_2$ suspension (Peech, 1965). A mixture of 0.2 M ammonium oxalate and 0.2 M oxalic acid adjusted to pH 3.0 was used to extract aluminum and iron (McKeague and Day, 1966 and Schwertmann, 1964) and both were determined by atomic absorption spectrophotometry. The wet oxidation method of Walkley and Black, as outlined by Allison (1965) was used to measure organic carbon. Finally, particle-size analysis was done by the hydrometer procedure (Bouyoucos, 1962).

2. Phosphorus Analyses

a. Colorimetric Procedure

All phosphorus determinations were done by the ascorbic acid method as outlined by Alexander and Robertson (1972).

b. Inorganic Phosphorus Fractionation

Inorganic phosphorus was fractionated by the Chang and Jackson procedure (1957) as modified by Glenn et al. (1959), except that 0.5 M NH_4F was adjusted to pH 8.5, as suggested by Fife (1959-63), instead of pH 8.2 (Table 2). Because of the large number of samples, resorption corrections recommended by some investigators (Fife, 1959-63; Rajendran and Sutton, 1970; Smith, 1965a, 1972; and Williams et al., 1967) were not applied.

Table 2   Fractionation procedure for inorganic phosphorus forms
           of the soil samples

Phosphorus form	Abbreviation	Extraction
Water-soluble plus loosely bound*	--	1 g of soil + 50 ml 1 M NH_4Cl for 30 min
Aluminum-bound	Al-P	50 ml 0.5 M $\bar{N}H_4F$ (pH 8.5) for 1 hr
Iron-bound	Fe-P	50 ml 0.1 M NaOH for 10 hr
Occluded	Occl-P	40 ml 0.3 M Na-citrate, 5 ml 1 M $NaHCO_3$, and 1 g Na-dithionite; and 50 ml 0.1 M NaOH for 10 hr
Calcium-bound	Ca-P	50 ml 0.25 M H_2SO_4 for 1 hr

* Phosphorus of this extract was not determined because analysis of
  several extracts showed less than 2 ppm P in the samples.

c. Organic Phosphorus

Organic phosphorus was determined by an ignition method proposed
by Saunders and Williams (1955), with minor modifications. Instead of
extracting a 2-g sample with 100 ml of 0.1 M H_2SO_4 for 16 1/2 hr, an
1-g sample was extracted with 50 ml of 1 M H_2SO_4 for 8 hr.

d. Total Phosphorus

A wet digestion procedure as outlined by Pawluk (1967) was used
for the total phosphorus determination, except that the sample was
ignited at 600C instead of 900C.

e. Extractable Phosphorus

Phosphorus in the 34 Ap horizon samples from the Tofield-Ryley
area was extracted by the NH_4F + H_2SO_4 and $NaHCO_3$ methods (Table 3).
These methods were selected because of their use in Western Canada.
Phosphorus in the Ap horizon samples used for the greenhouse experiment
was extracted by the above two methods and also by Calcium lactate +
HCl and EDTA methods (Table 3). The Calcium lactate procedure was
included since it had not been tested for Alberta soils and EDTA method
was included because in a previous study (Alexander and Robertson, 1972),
encouraging results were obtained for it.

D. GREENHOUSE EXPERIMENT

The greenhouse experiment using 20 Ap horizon samples, 10 Solonetzic
and 10 Chernozemic, was conducted to determine the response of barley

Table 3   Methods to determine extractable phosphorus of the Ap horizon
           samples

Extractant	pH of the extractant	Soil:Extractant (g) (ml)	Extraction time	Reference
0.03 M NH_4F + 0.015 M H_2SO_4	2.4	5.0:25	2 min	Miller and Axley, 1956 and Robertson, 1962
0.5 M $NaHCO_3$	8.5	2.5:50	30 min	Olsen et al., 1954
0.02 M Ca-lactate + 0.01 M HCl	3.7	1.0:50	2 hr	Warren and Cooke, 1965
5 m M disodium-EDTA*	4.7	2.5:50	1 hr	Alexander and Robertson, 1972

*   Ethylenediaminetetraacetic acid.

to added phosphorus in soils with varying levels of extractable (NH_4F + H_2SO_4) phosphorus. Three rates (0, 20, and 40 ppm) of phosphorus were applied as H_3PO_4 solution in a randomized block experiment with three replicates. Blanket rates of 100 ppm nitrogen, 80 ppm potassium, and 33 ppm sulphur were also applied. Nutrient solutions were mixed with the samples and each pot was filled with 1,000 g of soil sample. The samples were then brought to 0.10 bar moisture content and allowed to sit for five days. Each pot was seeded with 12 barley seeds (cultivar 'Galt') and after germination, the seedlings were thinned to five. The temperature in the room was kept at about 16C and artifical light was given for 17 hr per day until harvest. At six weeks from seeding, plant tops were harvested and dried at 70C for 24 hr to determine dry matter yield.

IV. RESULTS AND DISCUSSION

A. EXTRACTABLE PHOSPHORUS OF THE Ap HORIZON SAMPLES

The average $NH_4F + H_2SO_4$-P and $NaHCO_3$-P values for the 17 Solonetzic

samples are 27 and 25 ppm, whereas those for the 17 Chernozemic samples

are 11 and 12 ppm (Table 4), and the mean differences of the two groups

of samples are significant at $P = .01$. In addition, the average values

by the $NH_4F + H_2SO_4$ and $NaHCO_3$ methods are 35 and 23 ppm for the 10

Solonetzic and 16 and 12 ppm for the 10 Chernozemic samples used in the

greenhouse experiment (Table 5), and again the mean differences are

significant $(P = .01)$.

A comparison of the soils and the ASFTL data of extractable $(NH_4F +$

$H_2SO_4)$ phosphorus for the Tofield-Ryley area (Fig. 1) also reveals

generally higher levels of extractable phosphorus in the Solonetzic than

in the Chernozemic soils. Although there are exceptions to the general

trend, higher values are found in the center of the map where Solonetzic

soils predominate than on either side of the map where Chernozemic soils

predominate. Since the number of samples from the Solonetzic area

greatly exceeds that of the Chernozemic, no statistical analysis was

done to test whether the average values for the two groups are signifi-

cantly different. In this connection, it is pointed out that the ASFTL

values are for samples taken by farmers without any reference to the

Soil Orders.

Table 4   Extractable phosphorus of the Ap horizon samples from
the Tofield-Ryley area

Sample no*	Solonetzic samples		Chernozemic samples	
	NH_4F + H_2SO_4-P ppm	$NaHCO_3$-P ppm	NH_4F + H_2SO_4-P ppm	$NaHCO_3$-P ppm
1	29	27	11	14
2	10	14	8	10
3	19	18	8	9
4	42	33	21	17
5	41	39	10	12
6	34	33	7	9
7	30	33	3	7
8	20	32	14	13
9	28	33	11	13
10	25	18	3	5
11	24	17	2	6
12	25	19	6	9
13	30	26	12	12
14	14	15	23	16
15	8	11	10	9
16	42	31	23	24
17	35	29	11	12
Mean ± s.d.	27 ± 10**	25 ± 9	11 ± 6	12 ± 5

* The samples are not paired.

** The mean differences for 27,11 and 25,12 are significant at
P = .01.

Table 5   Extractable phosphorus of the Ap horizon samples used for
          the greenhouse experiment

Sample no	$NH_4F +$ H_2SO_4-P ppm	$NaHCO_3$-P ppm	Ca-lactate + HCl-P ppm	EDTA-P ppm
	SOLONETZIC SAMPLES			
1	31	22	34	27
2	9	8	8	8
3	12	8	11	9
4	48	26	44	35
5	40	28	45	30
6	26	21	32	23
7	45	30	41	30
8	51	32	45	30
9	45	32	48	38
10	42	27	38	26
Mean ± s.d.	35 ± 15*	23 ± 9	35 ± 14	26 ± 10
	CHERNOZEMIC SAMPLES			
1	13	9	30	25
2	20	14	30	23
3	10	9	13	11
4	24	18	39	32
5	4	9	9	8
6	26	15	41	32
7	15	12	24	18
8	8	6	11	9
9	14	12	34	25
10	28	18	31	25
Mean ± s.d.	16 ± 8	12 ± 4	26 ± 12	21 ± 9

* The mean differences for 35,16 and 23,12 are significant at P = .01;
  whereas, those for 35,26 and 26,21 are nonsignificant at P = .05.

Figure 1   Extractable phosphorus data (ppm) from the ASFTL
            (overlay) and soil map of the Tofield-Ryley area

            (See p. 26 and 27)

Legend for Figure 1

Solonetzic series   Camrose, Cam; Kavanagh, Kv; Ministik, Mk; and

                     Whitford, Wf

Chernozemic series   Angus Ridge, Ar; Falun, Fn; Mico, Mc; Malmo, Mo;

                     Peace Hills, Ph; Ponoka, Pk; and Rimbey, Rb

Luvisolic series   Cooking Lake, Ck; Maywood, Mw; and Uncas, Un

Gleysolic series   Prestville, Pr

Scale: 0.3 inch to 1 mile or 1 : 211,000

RANGES

BEAVERHILL

LAKE

Hastings Lake

BEAVERHILL LAKE
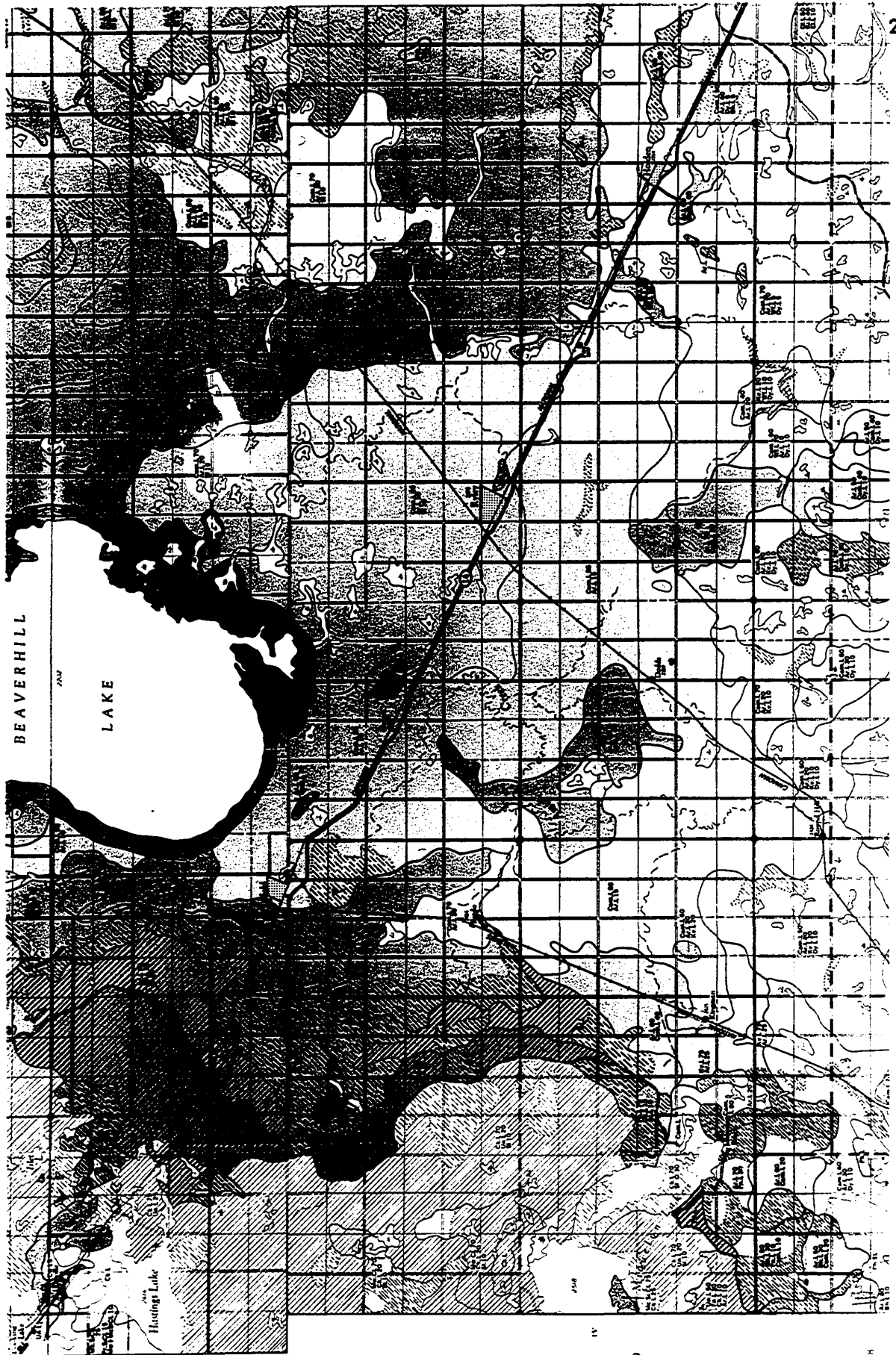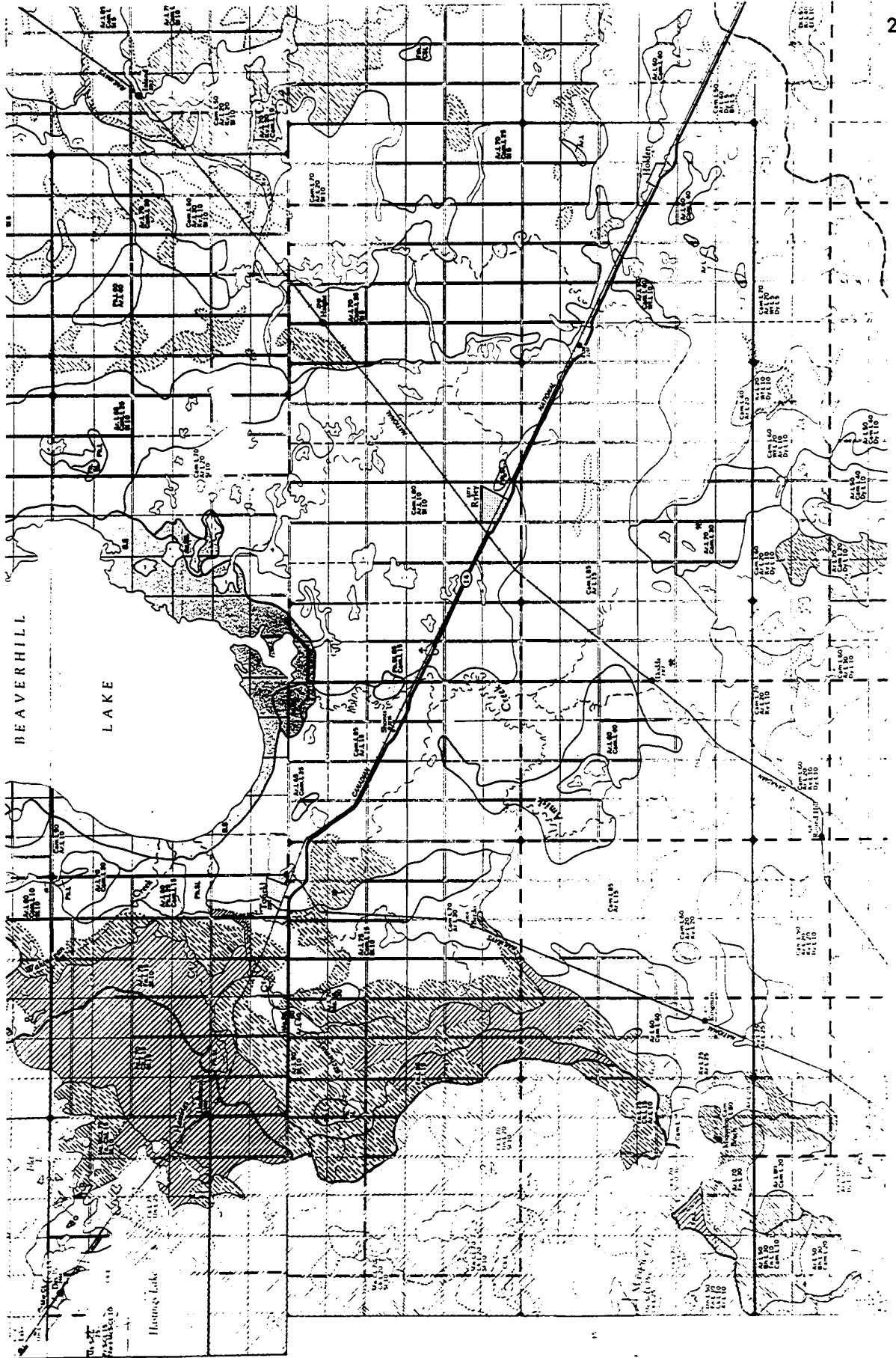
The average Ca-lactate + HCl-P and EDTA-P values are 35 and 26 ppm for the 10 Solonetzic and 26 and 21 ppm for the 10 Chernozemic samples used in the greenhouse experiment (Table 5). Here the differences in levels of extractable phosphorus between the two groups of samples are not as conspicuous as in the $NH_4F + H_2SO_4$ and $NaHCO_3$ methods, and they are not significantly different (P = .05).

When the extractable phosphorus values of the 20 Ap samples by the four methods are compared, there are close correlations (Table 6) between $NH_4F + H_2SO_4$-P values and $NaHCO_3$-P, Ca-lactate + HCl-P, and EDTA-P values. Taking all samples, $NaHCO_3$-P values are the most closely correlated with $NH_4F + H_2SO_4$-P values. In the Solonetzic samples, values by the $NaHCO_3$, Ca-lactate + HCl, and EDTA methods and in the Chernozemic samples, those by the $NaHCO_3$ method are the most closely correlated with $NH_4F + H_2SO_4$ values. Though there are close correlations between the values by the $NH_4F + H_2SO_4$ and other methods, when the extractable phosphorus values for each Ap sample are considered, there are exceptions from the general trend.

B. PHYSICAL AND CHEMICAL PROPERTIES OF THE SOIL PROFILES

The physical and chemical properties of individual profiles of the Maleb - Hemaruka - Halliday (Mb - Hu - Hd), Beaverhills - Camrose - Daysland (Bh - Cam - Dl), and Cooking Lake - Dnister - Nakamun (Ck - Dn - Nk) series are given in the Appendix (Tables A1 - A3). Only the average data of the three profiles of each series are shown in Figures 2 - 7.

Table 6   Correlation between the phosphorus extracted by NH_4F + H_2SO_4 and that by other extractants

Ap horizon samples and extractant	Correlation coefficient*
All samples (20)	
NaHCO$_3$	.97
Ca-lactate + HCl	.86
EDTA	.82
Solonetzic samples (10)	
NaHCO$_3$	.96
Ca-lactate + HCl	.96
EDTA	.93
Chernozemic samples (10)	
NaHCO$_3$	.92
Ca-lactate + HCl	.85
EDTA	.85

* All r values are significant at P = .01.

1. Soil pH, Oxalate Extractable Aluminum and Iron, Organic Carbon, and
   Particle-size Separates

   a. Soil pH

   Soil pH increases with depth in all the series except Daysland and
Cooking Lake (Fig. 2 - 4). In the Daysland and Cooking Lake profiles,
pH decreases to the upper B horizons and then increases with depth. The
lowest values are found in the Ah horizons of Hemaruka and Camrose; Ae
horizons of Hemaruka, Daysland, Dnister, and Nakamun; and in the Bt1
and Bt2 horizons of Cooking Lake profiles (Tables A1 - A3). The low
pH values in the upper sola of Solonetzic soils would be expected
because of varying degrees of solodization, and according to the System
of Soil Classification for Canada (Canada Department of Agriculture, 1970),
the soils of the Solonetzic Order, with rare exceptions, are to some
extent solodized. Brunelle (1969), in a study on the evolution of
profile development of some Solonetzic profiles, reported low pH values
for the Ae and upper Bnt horizons and indicated that maximum intensity
of pedogenesis occurred in these horizons.

   The pH of the Ah horizons increases from Solonetz to Solod to the
geographically associated Chernozemic profiles (Hemaruka to Halliday
to Maleb and Camrose to Daysland to Beaverhills) and this observation
is in accordance with that of Bowser et al. (1962b). Also, pH of the
Ae horizons tends to increase from the Solonetzic to the associated
Luvisolic profiles (Dnister and Nakamun to Cooking Lake). High
exchange acidity values for the surface horizons of Solonetzic soils,
reported by Bentley and Rost (1947) and Bowser et al. (1962b),
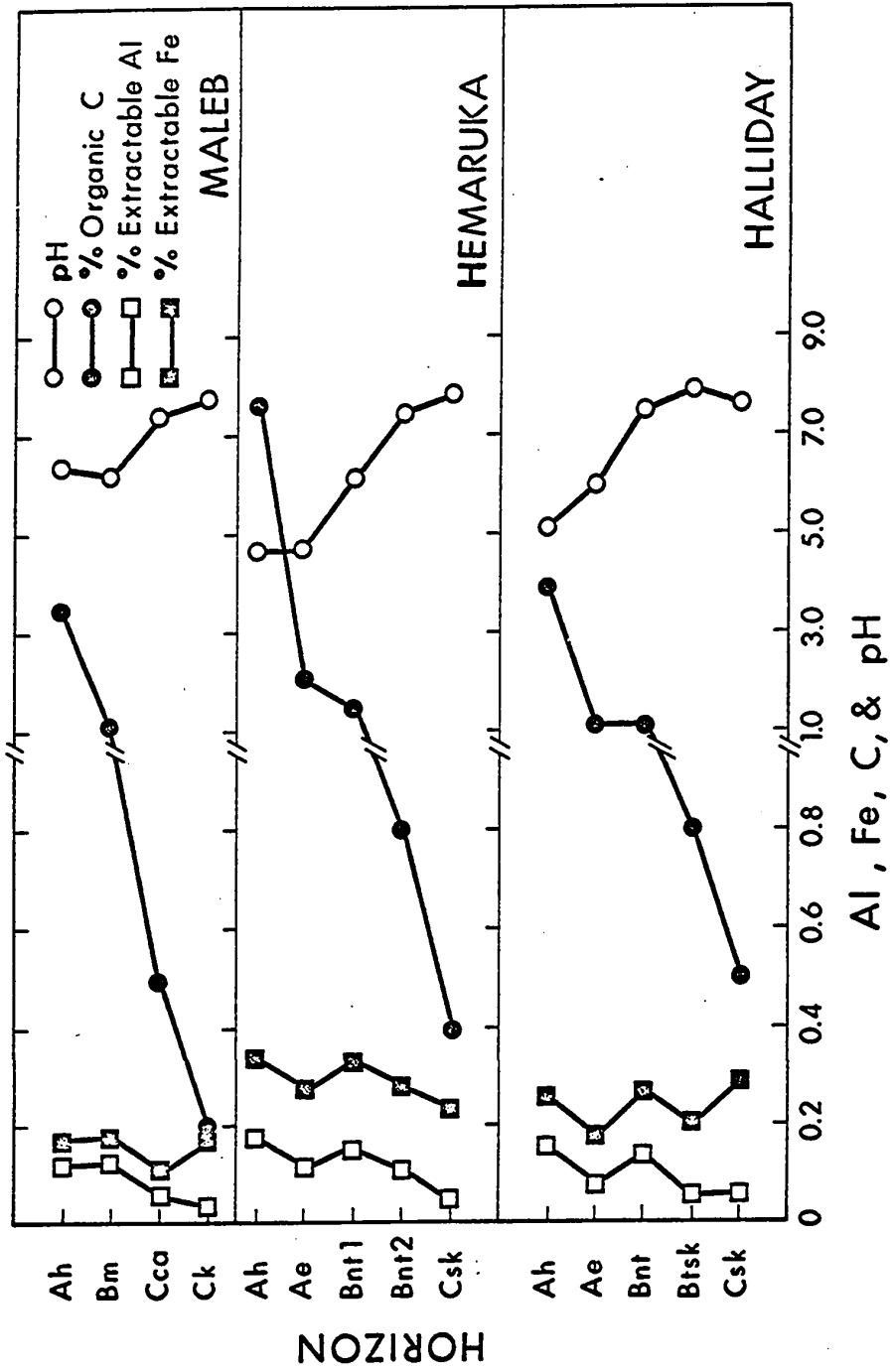
Figure 2   Chemical properties of the Maleb – Hemaruka – Halliday series
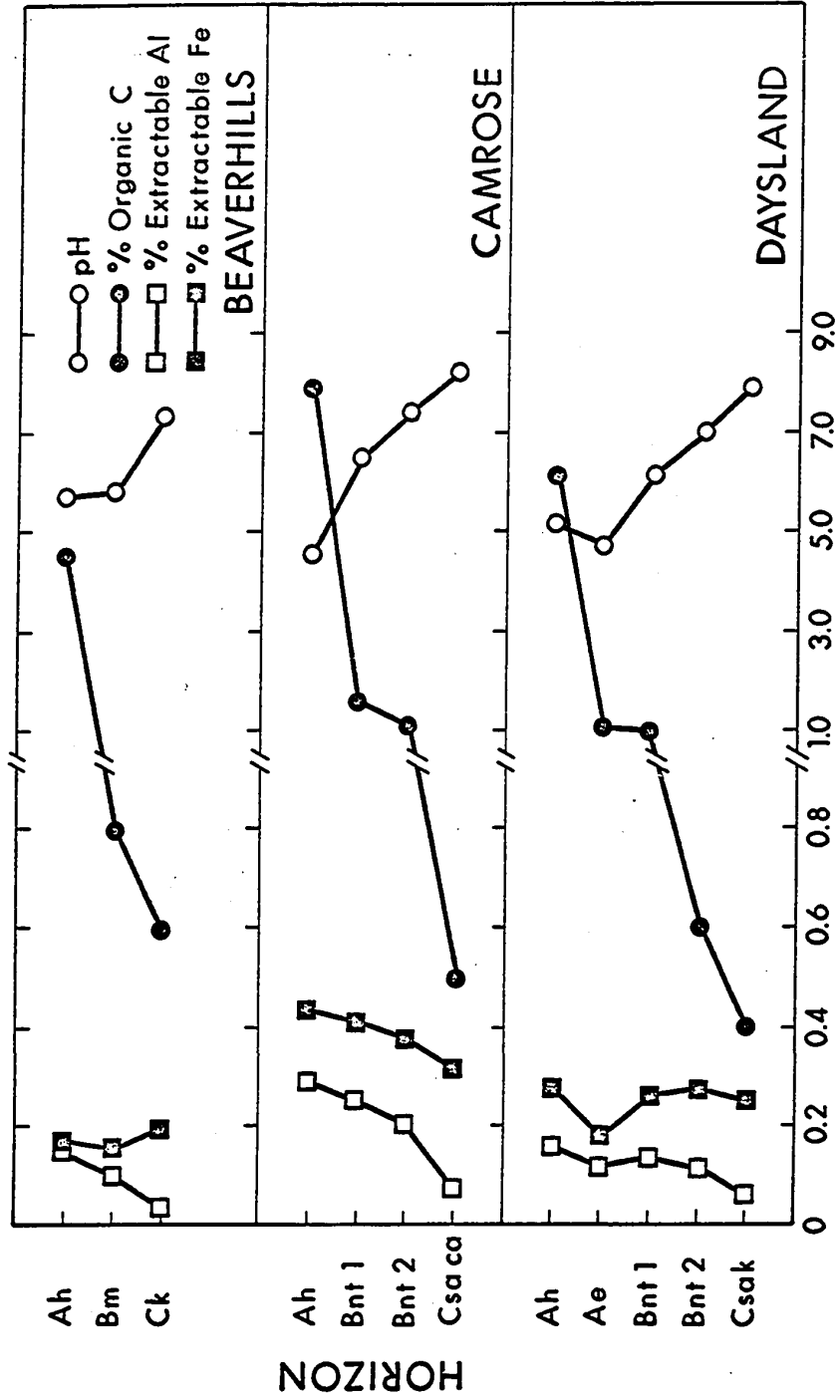
Figure 3   Chemical properties of the Beaverhills - Camrose - Daysland series
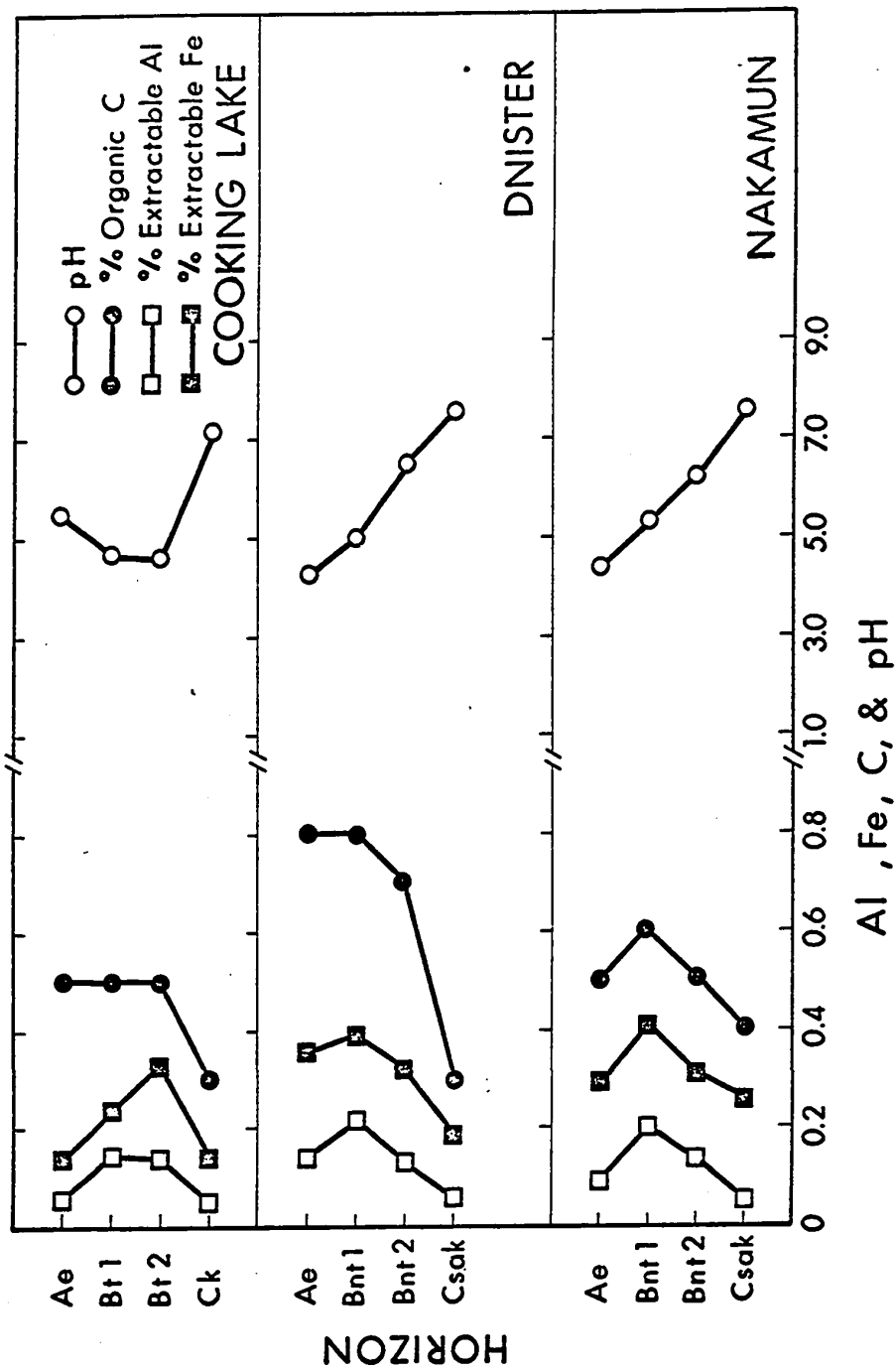
Figure 4   Chemical properties of the Cooking Lake – Dnister – Nakamun series

corroborate the low pH values observed for these horizons in the present study. The data from soil survey reports for various regions of Alberta (Odynsky, Wynnyk, and Newton, 1956; Odynsky et al., 1961; Peters and Bowser, 1960; Scheelar and Odynsky, 1968; and Wynnyk, Lindsay, and Odynsky, 1969) also reveal generally low pH values in the upper sola of Solonetzic soils.

b. Oxalate Extractable Aluminum and Iron

Extractable aluminum content tends to decrease with depth in the Maleb, Beaverhills, Camrose, and Daysland profiles and it decreases to Ae, increases to Bnt1, and then decreases with depth in the Hemaruka and Halliday profiles (Fig. 2 - 4). It tends to be greater in the Solonetzic than in the Chernozemic sola. In the Ck - Dn - Nk series, extractable aluminum contents are lower in the Ae and higher in the Bt1 and Bnt1 horizons. Here also, the Solonetzic sola tend to have higher percentages of extractable aluminum than do the associated Luvisolic sola. Invariably, all the C horizons have low levels of aluminum (below 0.10%). In general, higher contents of extractable aluminum are found in the more acid horizons. Relatively high levels of "free aluminum" were also reported by Arshad and Pawluk (1966), Brunelle (1969), and Mathieu (1960) for Solonetzic sola.

Oxalate extractable iron contents exceed those of oxalate extractable aluminum in the profiles (Fig. 2 - 4). In contrast to the extractable aluminum distribution, few general trends are apparent for the iron distribution of the profiles. Generally, lower levels of extractable iron are found in the Ae horizons and higher levels in the Bnt1 and Bt1

horizons. All the C horizons have higher percentages of extractable iron (0.15 - 0.30%) than aluminum (Tables Al - A3). As in the case of aluminum, the Solonetzic sola have greater contents of extractable iron than do the associated Chernozemic or Luvisolic sola. Relatively high levels of "free iron" were also reported by Arshad and Pawluk (1966), Brunelle (1969), and Mathieu (1960) for Solonetzic sola.

c. Organic Carbon

Carbon content decreases with depth in all the profiles (Fig. 2 - 4). In the Mb - Hu - Hd and Bh - Cam - Dl series, its contents are greater than 3.5% for the Ah horizons. But the Bm, Bnt2, Btsk, and C horizons of these series and all the horizons of the Ck - Dn - Nk series have much lower contents (below 1.5%). The Ae and Bnt1 horizons of the Mb - Hu - Hd and Bh - Cam - Dl series have intermediate contents. As a rule, the Solonetzic Ah horizons have higher carbon percentages than those of the associated Chernozemic profiles do and this observation is in agreement with that of Bowser et al. (1962b). However, the Ah horizons of the Solonetzic profiles are much thinner than those of Chernozemic profiles (Tables Al and A2) and thus the total organic carbon will usually be much lower in the Solonetzic Ah horizons.

d. Particle-size Separates

Generally, the percentages of sand and clay increase and those of silt decrease with depth in the profiles (Tables Al - A3). Texture of the surface horizons ranges from silt loam to clay loam. In the

Solonetzic profiles, per cent clay tends to be greater in the Bnt1 or Bnt2 than in the other horizons and the higher clay content in the B horizons is probably due to illuviation of clay from the surface horizons. An increase in sand percentage with depth was also reported by Brunelle (1969) for some Solonetzic profiles. Some of the soil survey reports of Alberta (Odynsky et al., 1961; Peters and Bowser, 1960; and Wynnyk et al., 1969) also depict similar trends in the distribution of particle-size separates of Solonetzic soils.

2. Inorganic Phosphorus Forms

Because of the large number of samples (134), resorption corrections were not applied to the Al-P and Fe-P forms. However, resorption studies done on four Solonetzic and four Chernozemic Ap horizon samples (Table A8) show that the proportion of sorbed phosphorus ranges from 0.15 to 0.50 (correction factor of 1.18 - 2.20) for the NH_4Cl extract and 0.05 to 0.18 (correction factor of 1.05 - 1.22) for the NH_4F extract. Since the NH_4Cl-P in these samples is less than 1 ppm, it would contribute at the most 2 ppm P to the Al-P form. The Al-P values will increase by 5 to 22% (1 - 4 ppm) and consequently an adjustment will have to be made in the Fe-P values. Because the extent of resorption would not markedly change the concentrations of Al-P and Fe-P forms, their values are not corrected for resorption of phosphorus during NH_4Cl and NH_4F extractions. The author is of the opinion that even if the recommended resorption corrections were applied, the data for inorganic phosphorus forms should be interpreted carefully. This is especially because of the redistribution of inorganic phosphorus

compounds during the extractions with relatively strong reagents such as 0.5 M NH_4F, 0.1 M NaOH, and 0.25 M H_2SO_4.

a. Aluminum-bound Phosphorus, Al-P

Al-P values for the surface horizons of the individual profiles (Tables Al - A3) vary from 8 to 51 ppm in the Mb - Hu - Hd and Bh - Cam - Dl series and 3 to 21 ppm in the Ck - Dn - Nk series. There is considerable variation in its values among the three profiles of some series, especially Camrose (8, 51, and 27 ppm for the three Ah horizons). In general, Al-P content decreases with depth (Fig. 5 - 7). Al-P constitutes a small component of the total phosphorus, and in most horizons its contribution is the lowest. The Ah horizons of the Solonetzic profiles tend to have higher concentrations of Al-P than those of the Chernozemic do and this is especially evident in the Halliday (Solod) and Camrose (Solonetz) profiles. Higher levels of this form were also reported by Haas (1964) and Mikanaev (1968) for the sola of some European Solonetzic profiles.

b. Iron-bound Phosphorus, Fe-P

Fe-P content, similar to that of Al-P, is greatest in the Ah horizons of the Mb - Hu - Hd and Bh - Cam - Dl series (Fig. 5 - 7). Generally, Solonetzic sola tend to have higher contents of Fe-P than do their associated Chernozemic sola. There is also considerable
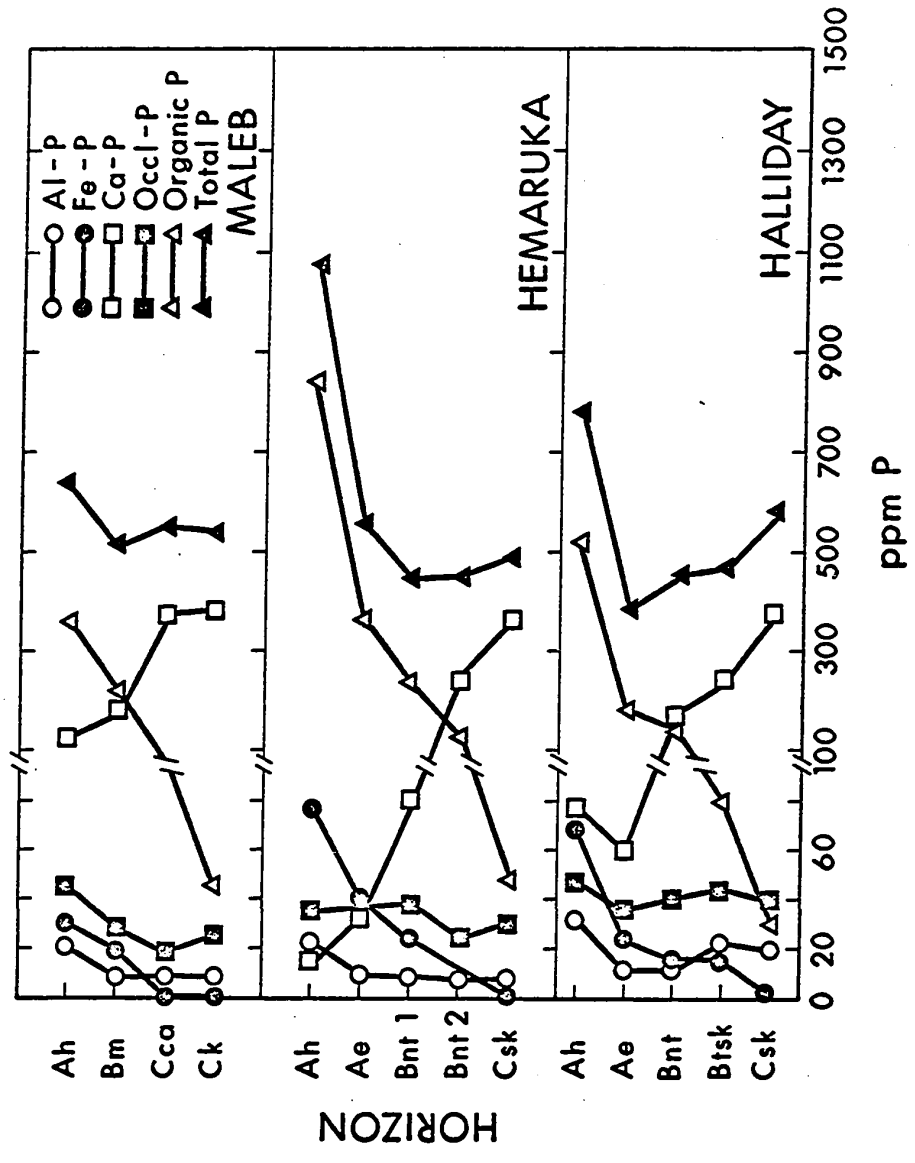
Figure 5   Phosphorus forms of the Maleb – Hemaruka – Halliday series
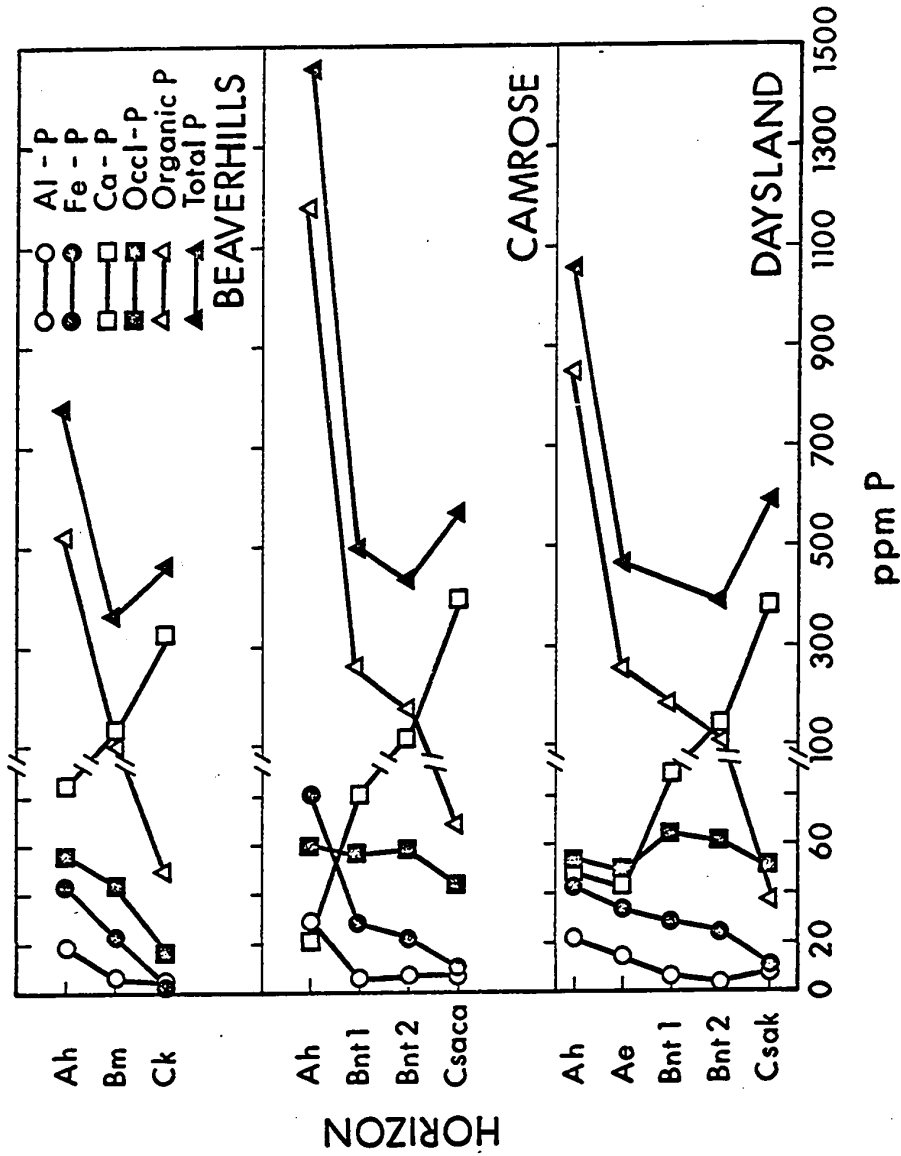
Figure 6   Phosphorus forms of the Beaverhills - Camrose - Daysland series
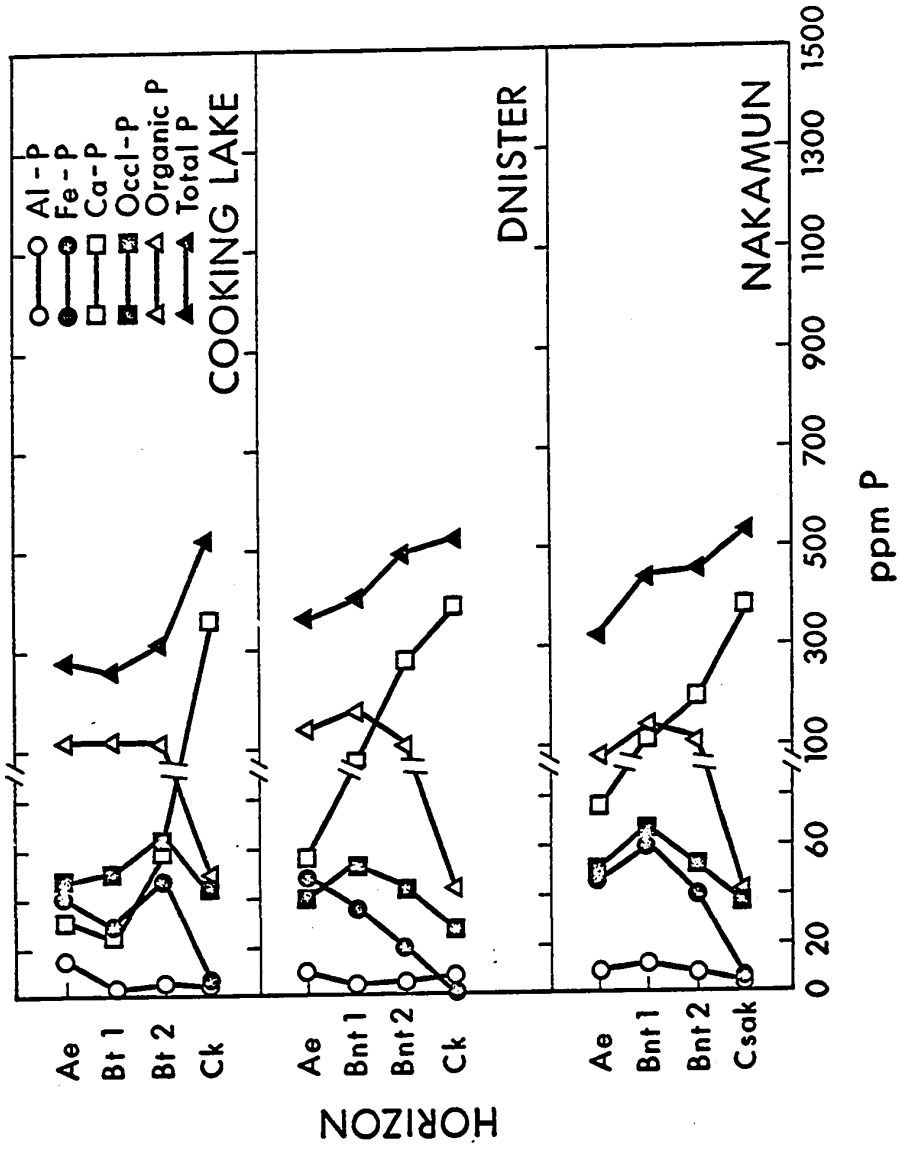
Figure 7   Phosphorus forms of the Cooking Lake - Dnister - Nakumun series

variation in its values among the three profiles of some series,
particularly Camrose and Daysland (Tables A1 - A3). In the Ck - Dn -
Nk series, there are no apparent trends in the distribution of this form.
Higher levels of Fe-P were also reported by Haas (1964) and Mikanaev
(1968) for the sola of some European Solonetzic profiles.

c. Calcium-bound Phosphorus, Ca-P

In contrast to the distributions of Al-P and Fe-P, Ca-P content
invariably increases with depth in the profiles (Fig. 5 - 7) and is
maximum in the C horizons where it constitutes more than 65% of the
total phosphorus. Generally, low concentrations of this form are found
in the more acid horizons and this is in contrast to the distributions
of Al-P and Fe-P. High acidity tends to preclude the presence of Ca-P
and this is supported by the low values of this form in the Ae horizons
of Halliday, Daysland, and Cooking Lake profiles (Tables A1 - A3).

The distributions of apatite in some Solonetzic and Chernozemic sola
of the Lake Edmonton basin (Arshad and Pawluk, 1966) corroborate the
trends in Ca-P distributions. Their data, though limited to the fine
sand separate of only four profiles, revealed higher percentages of
apatite in the Ah horizons of Chernozemic than in those of Solonetzic
profiles and this would support the greater concentrations of Ca-P
observed in the former than in the latter. The C horizons of all their
profiles had higher percentages of apatite than did the upper horizons
which would also agree with the preponderance of Ca-P in the C horizons
of the present study.

d. Occluded Phosphorus, Occl-P

Occl-P content decreases with depth in the Maleb and Beaverhills

profiles (Fig. 5 - 7). In the Solonetzes (Hemaruka and Camrose) of

the Mb - Hu - Hd and Bh - Cam - Dl series, its content tends to be

higher in the upper sola and in the Solods (Halliday and Daysland)

Occl-P tends to be lower in the Ae than in the Bnt horizons. In the

Ck - Dn - Nk series, the Btl and Bnt1 horizons contain the greatest

percentage of this form. The relatively high content of Occl-P in the

A and B horizons compared to the C horizons suggests that its accumu-

lation is related to pedogenic processes.

3. Organic, Residual, and Total Phosphorus

a. Organic Phosphorus

Organic phosphorus content decreases with depth in the Mb - Hu - Hd

and Bh - Cam - Dl series (Fig. 5 - 7) and is low in the C horizons

(below 75 ppm). Its content is greater in the Solonetzic Ah horizons

than in those of the Chernozemic profiles and this also agrees with the

higher percentages of organic carbon of the former. The Btl and Bnt1

horizons of the Ck - Dn - Nk series have slightly higher organic phos-

phorus concentrations than do the Ae horizons and its values for the

Btl, Bnt2, and C horizons of these series are similar to the values of

the B and C horizons of other series. The organic phosphorus values

of the Chernozemic horizons (Tables A1 and A2) are in agreement with

those reported by Dormaar (1961) for similar horizons of other Chernozemic

profiles of Alberta.

b. Residual Phosphorus

The difference between the total and the sum of Al-P, Fe-P, Ca-P,

Occl-P, and organic phosphorus is referred to as the residual phosphorus

(Enwezor and Moore, 1966). Earlier investigators have referred to this

form as "nonextractable," "insoluble," "inert," or "lattice" phosphorus

(Syers et al., 1969). According to Syers et al. (1969), the residual

phosphorus can have both a primary or secondary origin. Because the

values for this form are obtained by difference, there will be some

inaccuracies and, therefore, residual phosphorus data have to be

interpreted carefully. In most horizons, residual phosphorus content

is below 75 ppm and in only eight horizons is it above 100 ppm (Tables Al -

A3). There seems to be no general trend in the distribution of this

form in the profiles.

c. Total Phosphorus

Total phosphorus content decreases to the Bm and Bnt2 horizons and

then increases with depth in the Mb - Hu - Hd and Bh - Cam - Dl profiles

(Fig. 5 - 7). The reduction of phosphorus values in the B horizons is

probably due to the transfer of phosphorus to the A horizons by the

extensive root systems of grasses native to these profiles. In contrast,

total phosphorus tends to increase with depth in the Ck - Dn - Nk

profiles. Total phosphorus content varies from 414 to 684 (531 $\pm$ 61) ppm

in the C horizons of the profiles (Tables Al - A3). The values for the

C horizons are similar to those reported for other C horizons of Alberta

soils (Alexander and Robertson, 1968; Dormaar, 1961; Odynsky et al.,

1956, 1961; and Peters and Bowser, 1960).

C. PHYSICAL AND CHEMICAL PROPERTIES OF

THE 20 Ap HORIZON SAMPLES

1. Soil pH, Oxalate Extractable Aluminum and Iron, Organic Carbon,

    and Particle-size Separates

Soil pH varies from 4.5 to 4.8 in the 10 Solonetzic and 5.2 to

5.8 in the 10 Chernozemic Ap samples (Table A4) used for the greenhouse

experiment and the mean difference for the two groups is significant

at $P = .01$ (Table 7). The lower pH values of the Solonetzic Ap samples

are in agreement with those for the surface samples of the Solonetzic

profiles. Oxalate extractable aluminum content ranges from 0.16 to

0.23% for the Solonetzic and 0.11 to 0.21% for the Chernozemic Ap

samples and the mean difference for the two groups is also significant

$(P = .01)$. The ranges of oxalate extractable iron are 0.37 - 0.49% for

the Solonetzic and 0.22 - 0.51% for the Chernozemic Ap samples and as

in the case of aluminum, the mean difference is significant $(P = .01)$.

Again, as in the surface samples of the profiles, the extractable

aluminum and iron contents are higher in the Solonetzic than in the

Chernozemic Ap samples. Organic carbon content varies from 3.8 to 5.6%

in the Solonetzic and 3.0 to 6.6% in the Chernozemic Ap samples (mean

difference is significant at $P = .05$). The lower percentages of organic

carbon in the Solonetzic than in the Chernozemic Ap samples are in

contrast to those for the surface samples of the profiles, and may be

due to the mixing of Ae and Bnt horizons, low in carbon, into the top

15 cm of Solonetzic soils. The textures of the Ap samples range from

sandy clay loam to clay loam, most of them being clay loam, and the

Table 7   Physical and chemical properties of the Ap horizon samples
used for the greenhouse experiment

Soil property	Solonetzic sample mean	± s.d.	Chernozemic sample mean	± s.d.	Unpaired t-test
pH in 0.01 M CaCl$_2$	4.6	0.1	5.5	0.2	**
Oxalate extractable					
Al, %	0.20	0.02	0.15	0.03	**
Fe, %	0.44	0.04	0.32	0.10	**
Organic C, %	4.9	0.6	5.8	1.1	÷
Particle-size separates, %					
Sand	35	6	31	11	ns
Silt	35	4	35	6	ns
Clay	30	4	34	5	ns
Phosphorus forms, ppm					
Al-P	52	18	29	9	**
Fe-P	117	30	66	6	**
Ca-P	34	6	77	18	**
Occl-P	86	15	78	14	ns
Organic P	732	50	688	142	ns
Residual P	79	16	44	20	**
Total P	1,100	108	982	128	*

* The mean differences are significant at P = .05.

** The mean differences are significant at P = .01.

ns The mean differences are nonsignificant at P = .05.

mean differences of the sand, silt, and clay percentages for the

Solonetzic and Chernozemic groups are not significant (P = .05).

2. Inorganic Phosphorus Forms

The ranges of Al-P content are 20 - 75 ppm for the Solonetzic and

14 - 43 ppm for the Chernozemic Ap samples (Table A4) and the mean

difference for the two groups (Table 7) is significant at P = .01.

Fe-P content varies from 66 to 144 ppm in the Solonetzic and 55 to

74 ppm in the Chernozemic Ap samples and again the mean difference is

significant (P = .01). Therefore, the results for the Ap samples are

in agreement with those for the surface samples of the profiles, both

having higher levels of Al-P and Fe-P in the Solonetzic than in the

Chernozemic samples. Ca-P ranges from 23 to 46 ppm in the Solonetzic

and 50 to 103 ppm in the Chernozemic Ap samples (mean difference is

significant at P = .01). The distribution of Ca-P is also in accordance

with that for the surface samples of the profiles, and in both cases,

the Solonetzic have less Ca-P than the Chernozemic samples. There is

no difference in the distribution of Occl-P in the Solonetzic and

Chernozemic Ap samples (mean difference is not significant at P = .05).

3. Organic, Residual, and Total Phosphorus

Organic phosphorus content varies from 650 to 806 and 531 to 904 ppm

in the Solonetzic and Chernozemic Ap samples (Table A4), and the mean

difference is not significant at P = .05 (Table 7). Thus, in contrast

to the distribution of organic phosphorus in the surface samples of

the profiles, the difference between the Solonetzic and Chernozemic
groups is not marked and this may be due to the mixing of Ae and Bnt
horizons, low in organic phosphorus, into the top 15 cm of Solonetzic
soils. The residual phosphorus values range from 53 to 104 and 13 to
68 ppm in the Solonetzic and Chernozemic Ap samples and the mean
difference for the two groups is significant (P = .01). Finally,
total phosphorus content varies from 902 to 1,254 ppm in the Solonetzic
and 700 to 1,142 ppm in the Chernozemic Ap samples (mean difference is
significant at P = .05). Thus, the Solonetzic Ap samples have higher
concentrations of total phosphorus than the Chernozemic ones, and the
values for the Solonetzic Ap samples are in agreement with those reported
for the surface horizons of the Solonetzic profiles of the present study
as well as other studies (Odynsky et al., 1956, 1961 and Peters and
Bowser, 1960).

D. RESULTS OF THE GREENHOUSE EXPERIMENT

1. Dry Matter Yield of Barley

Average dry matter yields are 1.67, 2.08, and 2.20 g for the 10
Solonetzic and 1.84, 2.41, and 2.66 g for the 10 Chernozemic Ap samples
at the 0, 20, and 40 ppm phosphorus rates (Tables 8 and A9). In both
groups of samples, there are significant increases in yields (P = .01)
with phosphorus applications (Table 9). However, the average check
yields are not different for the Solonetzic and Chernozemic Orders and
the analysis of variance shows no difference in dry matter yields for
these Orders. Since Solonetzic samples have higher levels of NH_4F + H_2SO_4

Table 8   Average dry matter yield of barley*

Sample no	Yield, g / pot ppm P applied		
	0	20	40

SOLONETZIC SAMPLES

Sample no	0	20	40
1	2.01	2.23	2.28
2	1.08	1.94	2.32
3	1.09	1.91	2.16
4	2.04	2.30	2.06
5	1.69	2.10	2.31
6	1.31	1.66	1.80
7	1.40	1.68	1.91
8	1.89	2.04	2.14
9	2.24	2.68	2.65
10	1.92	2.23	2.41
Mean ± s.d.	1.67 ± .42	2.08 ± .31	2.20 ± .25

CHERNOZEMIC SAMPLES

Sample no	0	20	40
1	2.42	2.89	3.26
2	1.73	2.17	2.27
3	2.25	3.05	3.21
4	2.34	2.66	2.81
5	0.83	1.91	2.34
6	1.69	2.11	2.52
7	2.06	2.39	2.74
8	0.70	1.12	1.73
9	1.76	2.63	2.72
10	2.57	3.20	3.05
Mean ± s.d.	1.84 ± .64	2.41 ± .62	2.66 ± .47

* See Table A9 for the original dry matter yields.

Table 9   Analysis of variance for the dry matter yield of barley

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Orders	1	4.637	4.637	2.59
Orders x samples	18	32.27	1.793	
Treatments	2	14.95	7.475	68.6**
Orders x treatments	2	0.646	0.323	2.96
Orders x samples x treatments	36	3.929	0.109	
Replicates	2	0.242	0.121	4.65*
Orders x replicates	2	0.088	0.044	1.69
Orders x samples x replicates	36	0.930	0.026	
Treatments x replicates	4	0.253	0.063	4.20**
Orders x treatments x replicates	4	0.029	0.007	0.47
Orders x samples x treatments x replicates	72	1.045	0.015	
Total	179	59.02		

*   F-value is significant at P = .05.

** F-values are significant at P = .01.

extractable phosphorus, the check yields of these samples would be expected to be higher than those of the Chernozemic samples provided other factors remain optimum. Chemical analyses of plant tissue from the check pots (Tables A10 and A11) show similar percentages of nitrogen and phosphorus and the total uptake of these nutrients is also similar. Acidity and extractable aluminum levels would not seem to be restricting the check yields of the Solonetzic samples (M. Nyborg, personal communication). Nevertheless, reduced aeration, crusting, and puddling are frequently problems with Solonetzic soils in the greenhouse. The fact that even at the 40 ppm phosphorus rate, the yields from Solonetzic samples are not as high as those from Chernozemic samples (Tables 8 and A9) indicates that other factors are limiting the yield potential of the Solonetzic samples and these factors might account for the relatively lower check yields in spite of the higher levels of extractable (NH_4F + H_2SO_4) phosphorus in Solonetzic samples.

Looking at the yields at the 20 and 40 ppm phosphorus rates, it is apparent that the yield increases are less in the Solonetzic than in the Chernozemic samples. Although the effect of Orders is not significant (P = .10), the Order x treatment effect is significant at P = .10 (Table 9) because Solonetzic samples tend to have lower yields with applied phosphorus; and thus, they exhibit less response to applied phosphorus. While the average results tend to show less response in the Solonetzic than in the Chernozemic samples, Solonetzic samples 2 and 3 are exceptions to the general trend in that barley responds considerably in both samples. These samples are low in extractable phosphorus by all methods (Table 5) and they are also considerably lower in Al-P and

Fe-P forms compared to other Solonetzic samples (Table A4). It should be pointed out that the greenhouse samples were selected to represent the complete range of extractable phosphorus values found in the original 34 Ap horizon samples and that samples 2 and 3 are considerably lower in extractable phosphorus than the majority of Solonetzic samples.

Because the Solonetzic and Chernozemic soils are different in physical and chemical properties and in their yield potentials, the effect of applied phosphorus in these soils might be better shown by the relative or per cent yields (per cent yield = check yield x 100 / phosphorus pot yield). As per cent yield increases, the response of plants to applied phosphorus decreases. The average per cent yields at the 20 ppm phosphorus rate are 80 $\pm$ 13 and 74 $\pm$ 14, whereas those at the 40 ppm phosphorus rate are 76 $\pm$ 17 and 67 $\pm$ 17 for the Solonetzic and Chernozemic Ap samples. Since the per cent yields at 20 and 40 ppm phosphorus rates follow approximately similar trends for the 20 Ap samples, average per cent yields were calculated and they are 78 $\pm$ 14 and 71 $\pm$ 15 for the Solonetzic and Chernozemic samples. Even though the average per cent yields are not statistically significant (P = .05), Solonetzic samples tend to have the higher per cent yields suggesting a somewhat smaller response of barley to applied phosphorus.

Thus, based on the results of the greenhouse experiment, there is not a clear-cut difference in the status of plant-available phosphorus of Solonetzic and Chernozemic samples. Since it was shown that Solonetzic samples, on the average, have higher levels of extractable phosphorus by the NH_4F + H_2SO_4 and $NaHCO_3$ but not by the Ca-lactate + HCl and EDTA methods, the greenhouse results are not consistent with the former -

methods. However, in the interpretation of greenhouse results, it must be pointed out that the yield data presented are based on Ap horizon samples and the response of barley to applied phosphorus in the field may be different because the rooting volumes of Solonetzic soils are normally much smaller than those of Chernozemic soils.

2. Per cent Yield of Barley vs. Extractable Phosphorus of the 20 Ap
    Horizon Samples

Scatter diagrams for per cent yield of barley and extractable phosphorus by the four methods (Fig. 8) show that as the levels of extractable phosphorus increase, per cent yields increase or absolute response of barley to applied phosphorus decreases. There is a close linear correlation (Table 10) between the logarithms of extractable phosphorus by all methods and per cent yield of barley. Furthermore, the regression equations and correlation coefficients for all 20 Ap samples combined are not greatly different from those obtained for the Solonetzic and Chernozemic groups separately, though the $NaHCO_3$ method tends to be an exception from the general trend. Thus, the regression analysis reveals that there are good relationships between the levels of extractable phosphorus and per cent yield.

E. PHOSPHORUS FORMS VS. EXTRACTABLE PHOSPHORUS OF

THE 20 Ap HORIZON SAMPLES

Many investigators (Al-Abbas and Barber, 1964; Cho and Caldwell, 1959; Grigg, 1965; Hawkins and Kunze, 1965; Kaila, 1965; Khanna, 1967;

○ Chernozemic sample
● Solonetzic sample
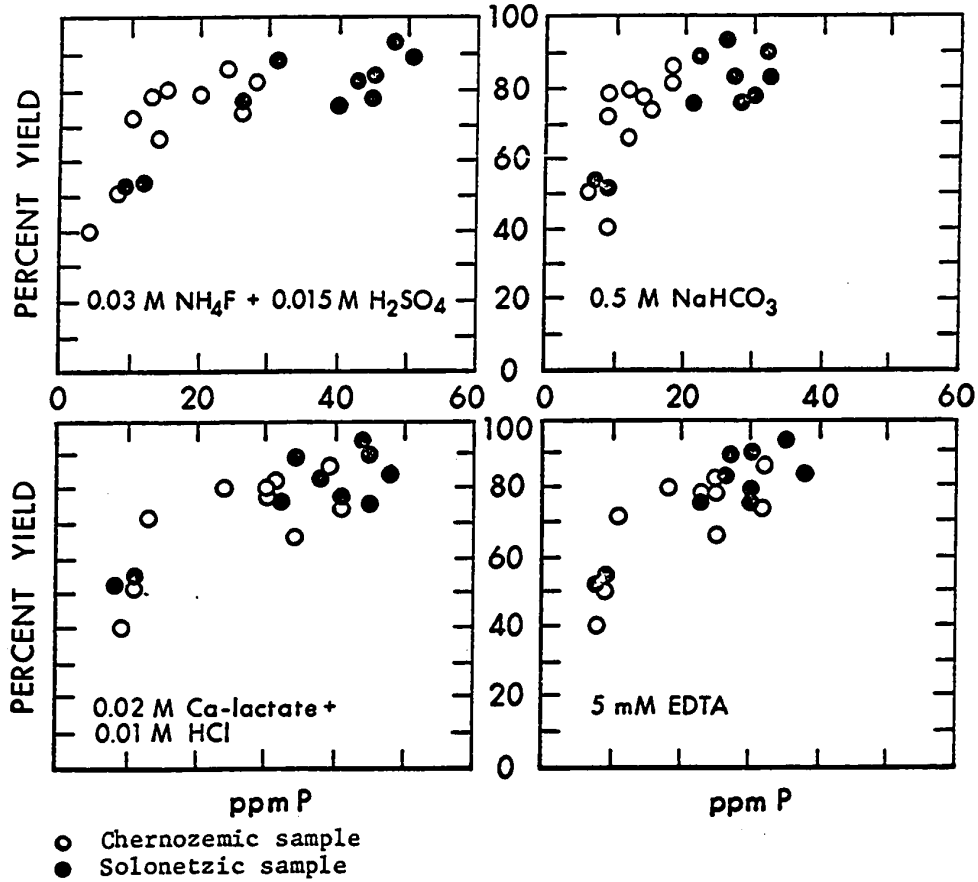
Figure 8   Scatter diagrams for the per cent yield of barley and
extractable phosphorus by the four methods

Table 10. Regression and correlation between the logarithms of
extractable phosphorus (x) and per cent yield of barley (y)

Ap horizon samples and extractant	Regression equation*		Correlation coefficient**
	m	b	
All samples (20)			
$NH_4F + H_2SO_4$	40	22	.85
$NaHCO_3$	48	17	.77
Ca-lactate + HCl	48	5.2	.86
EDTA	55	1.6	.87
Solonetzic samples (10)			
$NH_4F + H_2SO_4$	49	4.3	.91
$NaHCO_3$	55	4.9	.88
Ca-lactate + HCl	47	8.0	.91
EDTA	56	1.7	.92
Chernozemic samples (10)			
$NH_4F + H_2SO_4$	49	15	.88
$NaHCO_3$	67	-0.2	.70
Ca-lactate + HCl	49	4.2	.81
EDTA	53	3.7	.81

* $y = m \log x \pm b.$

** All r values except 0.70 are significant at P = .01;
0.70 is significant at P = .05.

Kurtz and Quirk, 1965; Pratt and Garber, 1964; Tripathi et al., 1970;
and Tyner and Davide, 1962) have attempted to indirectly show the
importance of various phosphorus forms to plants by correlating the
amounts of forms with extractable phosphorus measured by different soil
test reagents. In the present study, amounts of the various phosphorus
forms and extractable phosphorus by the $NH_4F + H_2SO_4$, $NaHCO_3$, Ca-lactate
+ HCl, and EDTA methods were available for the 20 Ap horizon samples;
and hence, it was decided to run a correlation analysis for these para-
meters.

Generally, the levels of extractable phosphorus by all methods are
closely correlated with Al-P (Table 11), which is the first form obtained
in the fractionation scheme. Several researchers (Dunbar and Baker, 1965;
Machold, 1963; MacKenzie, 1962; Rotini and El-Nennah, 1971; Tandon and
Kurtz, 1968; and Weir and Soper, 1962) have demonstrated the quick
isotopic exchangeability of Al-P compared to Fe-P and Ca-P forms.
Omanwar (1970), in a study on some Ap samples of Alberta soils, including
three Ap samples used in the present investigation, reported close
correlations among several parameters including A, Ee (labile phosphorus),
$NH_4F + H_2SO_4$-P, $NaHCO_3$-P, and Al-P values. The Ee values were about
60% of the $NH_4F + H_2SO_4$-P values, whereas they were similar in magnitude
to $NaHCO_3$-P values. Based on the magnitude of the values obtained
and the close correlations observed, he suggested that $NH_4F + H_2SO_4$
removed most of the labile and some nonlabile phosphorus, whereas
$NaHCO_3$ removed most of the labile phosphorus. Since in the present
study Al-P values are approximately twice the $NH_4F + H_2SO_4$-P and

Table 11. Correlation between the phosphorus forms and extractable phosphorus of the 20 Ap horizon samples

Extractant	$NH_4F + H_2SO_4$	$NaHCO_3$	Ca-lactate + HCl	EDTA
Phosphorus form		Correlation coefficient		
Al-P	.97**	.98**	.86**	.81**
Fe-P	.79**	.86**	.65**	.57**
Ca-P	-.43	-.46*	-.06	.02
Occl-P	.55**	.56**	.65**	.62**
Organic P	.01	.10	-.18	-.20
Residual P	.52*	.59**	.23	.20
Total P	.43	.53*	.25	.20

* Significant at P = .05.

** Significant at P = .01.

$NaHCO_3$-P values, it can be assumed that Al-P probably includes most of the labile phosphorus.

The next closest correlations are obtained for Fe-P form. Isotopic exchange studies, already mentioned, have also demonstrated the quick isotopic exchangeability of Fe-P compared to Ca-P. After the removal of most of the labile phosphorus by NH_4F extraction (Al-P), NaOH extraction for Fe-P must dissolve some of the nonlabile phosphorus and this is reflected in the absolute values of Fe-P which are approximately four times those of extractable phosphorus by all the methods.

Since Ca-P is less isotopically exchangeable than Al-P and Fe-P forms, close correlations are not obtained for Ca-P and extractable phosphorus. In the case of NH_4F + H_2SO_4 and $NaHCO_3$ methods, there are negative correlations. Occl-P is better correlated than Ca-P with extractable phosphorus by all methods. Similarly, residual phosphorus is better correlated than Ca-P with extractable phosphorus by NH_4F + H_2SO_4 and $NaHCO_3$ methods. In general, the organic and total phosphorus values are 20 to 50 times higher than extractable phosphorus values and therefore, the correlation coefficients do not reveal any trend.

The close correlations obtained for Al- and Fe-P and extractable phosphorus can also be explained on the basis of the composition of the four extractants (Table 3). These extractants would dissolve portions of Al-P and Fe-P (which are more labile than other inorganic phosphorus forms), the more soluble calcium phosphates, and other phosphorus forms.

V. GENERAL DISCUSSION

One of the aims of this investigation was to find if the higher levels

of extractable (0.03 M NH_4F + 0.015 M H_2SO_4) phosphorus are definitely

associated with Solonetzic soils in a predominant Solonetzic area.

The NH_4F + H_2SO_4-P values of the 34 randomly selected Ap samples

(0 - 15 cm) from the Tofield-Ryley area show a clear difference in

extractable phosphorus levels of the Solonetzic and Chernozemic samples.

In general, Solonetzic samples have more than twice the amount of

extractable phosphorus found in the Chernozemic samples. Results of the

0.5 M $NaHCO_3$ method also show similar trends; and therefore, the obser-

vation of an area of higher extractable phosphorus values would have been

made by either of the methods.

Comparison of the extractable (NH_4F + H_2SO_4) phosphorus data from

the Soil and Feed Testing Laboratory with the soils of the Tofield-

Ryley area reveals generally higher levels of extractable phosphorus in

the Solonetzic than in the Chernozemic soils. The results of the 20 Ap

samples used for the greenhouse experiment also indicate that there is

a clear difference in the levels of NH_4F + H_2SO_4 as well as $NaHCO_3$

extractable phosphorus of Solonetzic and Chernozemic samples. However,

the 0.02 M Ca-lactate + 0.01 M HCl and $5m$ M disodium-EDTA extractable

phosphorus values do not show a clear difference between the two groups.

Until the suitability of Ca-lactate + HCl and EDTA as soil test reagents

for extractable phosphorus is examined for Alberta soils, one would use

either the $NH_4F + H_2SO_4$ or $NaHCO_3$ method. Since both the latter methods show that Solonetzic samples have higher levels of extractable phosphorus than do the adjacent Chernozemic samples, the higher values obtained cannot be interpreted as an artifact of the $NH_4F + H_2SO_4$ method.

The second aim was to seek an explanation for the higher levels of extractable ($NH_4F + H_2SO_4$) phosphorus in Solonetzic soils, through the physical and chemical properties of these soils. Several factors may control the extractable phosphorus status of soils: e.g. fertilizer practices, phosphorus content of the parent material, distribution of particle-size separates, content of organic phosphorus of the surface horizons, acidity, contents of extractable aluminum and iron, and inorganic phosphorus forms.

At the time of sampling, fertilizer history of each site was obtained from the farmer. Generally, the farmers have applied phosphorus fertilizers two to five times since the breaking of soils from the virgin conditions and there seemed to be no evidence for different fertilizer history on the Solonetzic than on the Chernozemic soils of the Tofield-Ryley area. Therefore, it is not possible to explain the difference in extractable phosphorus levels between the Solonetzic and Chernozemic soils by higher application of phosphorus fertilizers in the former than in the latter.

Another possibility is that breaking the soils from the virgin state and subsequent cultivation has resulted in an increase of extractable phosphorus mainly through mineralization of organic phosphorus. Since the extractable phosphorus data for the virgin samples corresponding

to the Ap samples are not available, it is difficult to determine whether cultivation has an effect in increasing extractable phosphorus. Any influence of organic phosphorus on extractable phosphorus would have to be indirect, because extractable phosphorus of the Ap samples is measured by soil tests which do not take into account organic phosphorus. For example, it may mineralize faster in the Solonetzic than in the Chernozemic samples. Since it has been shown that the Solonetzic and Chernozemic samples are not greatly different in organic carbon and since they are not much different in organic phosphorus contents, it seems unlikely that organic phosphorus would contribute more to extractable phosphorus in the former than in the latter.

Another possible reason for the higher levels of extractable phosphorus in Solonetzic soils is that total phosphorus content may be greater in the parent material of these than in their geographically associated Chernozemic soils. The parent material is important because, under natural conditions, all phosphorus in soils must come from it (Walker, 1965). All Ap samples were taken from an area where the parent material for the soils is glacial till. Total phosphorus contents in the C horizons of the profiles (552 ± 79 and 499 ± 48 ppm for the Solonetzic and Chernozemic C horizons) and the results of previous investigations on similar glacial till (Alexander and Robertson, 1968; Dormaar, 1961; Odynsky et al., 1956, 1961; and Peters and Bowser, 1960) show the uniformity in total phosphorus content of the parent material. Accordingly, differences in total phosphorus content of the parent material cannot account for the differences in extractable phosphorus levels of Solonetzic and Chernozemic soils.

It is possible that differences in particle-size distributions can account for the differences in the extractable phosphorus levels of soils. Since the amorphous materials accumulate in clay and silt, these separates contribute the most to the extractable phosphorus of soils. The particle-size distributions are not greatly different for the Solonetzic and Chernozemic Ap samples, most of them being clay loam in texture. Consequently, the higher levels of extractable phosphorus in Solonetzic soils cannot be explained by the differences in the contents of clay and silt.

Associated with particle-size distribution is the influence that the kind of clay minerals might have on the extractable phosphorus levels of soils. Even though no mineralogical analyses were done on the Solonetzic Ap samples, such analyses have been done on some Solonetzic soils of Alberta (Arshad and Pawluk, 1966; Brunelle, 1969; and Mathieu, 1960) and they indicate that the principal clay mineral in Solonetzic soils is montmorillonite. The associated Chernozemic soils also have montmorillonite as the dominant clay mineral. Thus, since the Solonetzic and Chernozemic samples used in this study probably have similar clay mineral suites, it seems unlikely that the higher levels of extractable phosphorus in the former are due to the influence of clay minerals in them.

What is the importance of acidity, oxalate extractable aluminum and iron, and inorganic phosphorus forms in controlling the extractable phosphorus levels of soils? The Solonetzic Ap and the surface samples of the profiles are more acidic than the Chernozemic ones; and the former have higher levels of oxalate extractable aluminum and iron than

do the latter samples. For example, Solonetzic Ap samples have 33 - 38%
more extractable aluminum and iron than do the Chernozemic samples.
The results of the phosphorus fractionation of the profiles show Al-P
and Fe-P as the preponderant forms in the Solonetzic sola. Also, the
data of the Ap samples show clearly higher levels of Al-P and Fe-P
and lower levels of Ca-P in the Solonetzic than in the Chernozemic
samples. Thus, both the profile and Ap sample data indicate an increase
of Al-P and Fe-P with an increase in acidity. The high acidity and
intense weathering conditions in the upper sola of the Solonetzic soils
(Arshad and Pawluk, 1966 and Brunelle, 1969) would result in higher
levels of extractable aluminum and iron and these in turn seem to
account for the higher levels of Al-P and Fe-P in the Solonetzic than
in the Chernozemic soils. This is also supported by the significant
correlations (P = .05) between the extractable aluminum and Al-P in the
profile samples as well as those between the extractable iron and Fe-P
in both the profile and Ap samples.

Since the main difference in the distributions of inorganic phos-
phorus forms of the Solonetzic and Chernozemic sola and Ap samples is
in the contents of Al-P and Fe-P, it seemed desirable to consider the
relationship of these forms to extractable phosphorus of the Solonetzic
soils. The results of this investigation and those of previous ones
(Alexander and Robertson, 1968, 1972) do show close correlations between
the Al- and Fe-P forms and the extractable phosphorus measured by
$NH_4F + H_2SO_4$, $NaHCO_3$, Ca-lactate + HCl, and EDTA methods. Therefore,
the higher levels of Al-P and Fe-P forms in Solonetzic soils seem to
account for the higher levels of extractable phosphorus in them.

The third aim of this investigation was to ascertain the importance of the higher levels of extractable (NH_4F + H_2SO_4) phosphorus of Solonetzic soils to barley growth in a greenhouse experiment. The average dry matter yields of the check pots are not different for the Solonetzic and Chernozemic samples and there are significant (P = .01) increases in yields with phosphorus applications in both groups. Both the per cent yields and the significance (P = .10) of Order x treatment effect suggest a somewhat smaller response of barley to applied phosphorus in the Solonetzic than in the Chernozemic samples. Thus, though the NH_4F + H_2SO_4 and $NaHCO_3$ but not the Ca-lactate + HCl and EDTA methods separate the Solonetzic and Chernozemic Orders in terms of extractable phosphorus levels, there is not a clear-cut difference in the status of plant-available phosphorus of these Orders.

Comparison of the extractable phosphorus levels by the four methods and per cent yield of barley reveals close correlation between these parameters. Even though the correlation is better for the Solonetzic than for the Chernozemic samples, it holds good for the samples taken as a group. Furthermore, regression equations between the extractable phosphorus and per cent yield for the samples as a group are not greatly different from those obtained for the Solonetzic and Chernozemic samples separately. Since the relationship between these parameters is consistently better for the Solonetzic than for the Chernozemic samples, the feasibility of using the same method to measure extractable phosphorus from soils of different physical and chemical properties, as in the Solonetzic and Chernozemic soils, needs further examination. Field work to assess this question is currently in progress at the Tofield-Ryley and Camrose-Stettler areas.

VI. CONCLUSIONS

Thirty-four Ap samples from the Tofield-Ryley area and 20 Ap samples
used for the greenhouse experiment demonstrate markedly higher levels
of extractable phosphorus by the two methods currently used in Western
Canada ($NH_4F + H_2SO_4$ and $NaHCO_3$) in the Solonetzic than in the Cherno-
zemic samples. Comparison of the Agricultural Soil and Feed Testing
Laboratory's data with the soils of the Tofield-Ryley area reveals
generally higher levels of $NH_4F + H_2SO_4$ extractable phosphorus in the
Solonetzic compared to the Chernozemic soils. The Ca-lactate + HCl-P
and EDTA-P values also show more extractable phosphorus in the Solonetzic
than in the Chernozemic Ap samples used for the greenhouse experiment,
though here the differences in levels of extractable phosphorus are
not as marked as in the $NH_4F + H_2SO_4$ and $NaHCO_3$ methods.

Hence, the Solonetzic soils have generally higher levels of
extractable phosphorus than do the associated Chernozemic soils.

The high acidity and intense weathering conditions in the upper
sola of Solonetzic soils seem to have resulted in relatively high
contents of oxalate extractable aluminum and iron and these probably
account for the higher levels of Al-P and Fe-P and lower levels of
Ca-P in the Solonetzic than in the Chernozemic sola. Irrespective of
the soils, Ca-P is the preponderant form in all C horizons. Generally,
Solonetzic Ah horizons have higher percentages of organic carbon and
organic phosphorus than do the adjacent Chernozemic Ah horizons,

though this trend is not apparent in the Ap samples. Among the phosphorus forms, contents of Al-P and Fe-P were the most closely correlated with the levels of extractable phosphorus in the Ap samples showing the importance of Al-P and Fe-P as sources of extractable phosphorus in these samples.

Therefore, the higher levels of extractable phosphorus in the Solonetzic than in the Chernozemic soils seem to be due to the higher contents of Al-P and Fe-P forms in the former.

Results of the greenhouse experiment with barley show no difference in the average dry matter yields of the check pots for the Solonetzic and Chernozemic samples. However, there are significant (P = .01) increases in yields with phosphorus applications in both groups. Both the per cent yields and the significance (P = .10) of Order x treatment effect suggest that barley tends to respond less to applied phosphorus in the Solonetzic than in the Chernozemic samples.

Thus, though the $NH_4F + H_2SO_4$ and $NaHCO_3$ methods demonstrate a clear difference in the extractable phosphorus status of Solonetzic and Chernozemic soils, greenhouse results show no clear-cut difference in the status of plant-available phosphorus of these Orders.

Comparison of extractable phosphorus measured by the four methods with per cent yield of barley reveals close correlation between these parameters for both the Solonetzic and Chernozemic samples, though the correlation coefficients were better for the former.

VII. REFERENCES

Al-Abbas, A. H. and Barber, S. A. 1964. A soil test for phosphorus based upon fractionation of soil phosphorus. 1. Correlation of soil phosphorus fractions with plant-available phosphorus. Soil Sci. Soc. Amer. Proc. 28: 218-221.

Alexander, T. G. and Robertson, J. A. 1968. Inorganic phosphorus forms in some Alberta soils as related to soil development, parent material and available phosphorus. Can. J. Soil Sci. 48: 289-295.

Alexander, T. G. and Robertson, J. A. 1972. EDTA extractable phosphorus in relation to available and inorganic phosphorus forms in soils. Soil Sci. 114: 69-72.

Allison, L. E. 1965. Organic carbon. In "Methods of Soil Analysis" p. 1367-1378. Pub. Amer. Soc. Agron., Wisconsin, USA.

Arshad, M. A. and Pawluk, S. 1966. Characteristics of some Solonetzic soils in the glacial Lake Edmonton basin of Alberta. 1. Physical and chemical. 2. Mineralogy. J. Soil Sci. 17: 36-55.

Bentley, C. F. and Rost, C. O. 1947. A study of some Solonetzic soil complexes in Saskatchewan. Sci. Agr. 27: 293-313.

Blanchar, R. W. and Caldwell, A. C. 1964. Phosphorus uptake by plants and readily extractable phosphorus in soils. Agron. J. 56: 218-221.

Bornemisza, E. and Fassbender, H. W. 1970. Uptake of fertilizer phosphate from nine soils from the humid tropics. Agrochimica 14: 259-268.

Bouyoucos, G. B. 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54: 464-465.

Bowser, W. E., Kjearsgaard, A. A., Peters, T. W., and Wells, R. E. 1962a. "Soil Survey of Edmonton Sheet (83-H)." Univ. of Alberta Bull. No. SS-4.

Bowser, W. E., Milne, R. A., and Cairns, R. R. 1962b. Characteristics of the major soil groups in an area dominated by Solonetzic soils. Can. J. Soil Sci. 42: 165-179.

Bromfield, S. M. 1967a. Phosphate sorbing sites in acid soils. 1. An examination of the use of ammonium fluoride as a selective extractant for aluminum-bound phosphate in phosphated soils. Aust. J. Soil Res. 5: 93-102.

Bromfield, S. M. 1967b. An examination of the use of ammonium fluoride as a selective extractant for aluminum-bound phosphate in partially phosphated systems. Aust. J. Soil Res. 5: 225-234.

Bromfield, S. M. 1970. The inadequacy of corrections for resorption of phosphate during the extraction of aluminum-bound soil phosphate. Soil Sci. 109: 388-390.

Brunelle, A. 1969. Evaluation of profile development in some Solonetzic soils of south-central Alberta. M. Sc. Thesis, Univ. of Alberta, Edmonton.

Cairns, R. R. 1961. Some chemical characteristics of a Solonetzic soil sequence at Vegreville, Alberta, with regard to possible amelioration. Can. J. Soil Sci. 41: 24-34.

Cameron, D. R. and Toogood, J. A. 1970. Computer mapping of Alberta soil test data. Can. J. Soil Sci. 50: 1-7.

Canada Department of Agriculture. 1970. "The System of Soil Class-
ification for Canada." Pub. Queen's Printer for Canada.

Chang, S. C. and Jackson, M. L. 1957. Fractionation of soil phosphorus.
Soil Sci. 84: 133-144.

Chang, S. C. and Jackson, M. L. 1958. Soil phosphorus fractions in
some representative soils. J. Soil Sci. 9: 109-119.

Cho, C. M. and Caldwell, A. C. 1959. Forms of phosphorus and fixation
in soils. Soil Sci. Soc. Amer. Proc. 23: 458-460.

Dahnke, W. C., Malcolm, J. L., and Menendez, M. E. 1964. Phosphorus
fractions in selected soil profiles of El Salvador as related to
their development. Soil Sci. 98: 33-38.

Datta, N. P. and Khera, M. S. 1969. Phosphorus soil tests based upon
correlations with inorganic phosphorus fractions and greenhouse
tests. J. Indian Soc. Soil Sci. 17: 191-196.

Dean, L. A. 1938. An attempted fractionation of the soil phosphorus.
J. Agr. Sci. 28: 234-246.

Dmitrenko, P. A. and Shturmova, V. S. 1953. Characteristics of the
distribution of phosphorus in the horizons of Solonetzes of the
southern USSR. Abstr. in Soils Fert. 16: 1298.

Dormaar, J. F. 1961. A study concerning the distribution of organic
phosphorus in soils. Ph. D. Thesis, Univ. of Alberta, Edmonton.

Dunbar, A. D. and Baker, D. E. 1965. Use of isotopic dilution in a
study of inorganic phosphorus fractions from different soils.
Soil Sci. Soc. Amer. Proc. 29: 259-262.

Ehrlich, W. A. and Smith, R. E. 1958. Halomorphism of some clay soils in Manitoba. Can. J. Soil Sci. 38: 103-113.

Ellis, J. H. and Caldwell, O. G. 1935. Magnesium clay Solonetz. 3rd Int. Cong. Soil Sci. 1: 348-350.

Enwezor, W. O. and Moore, A. W. 1966. Phosphorus status of some Nigerian soils. Soil Sci. 102: 322-328.

Fife, C. V. 1959-63. An evaluation of ammonium fluoride as a selective extractant for aluminum-bound soil phosphate. 1. Preliminary studies on non-soil systems, 2. Preliminary studies on soils, 3. Detailed studies on selected soils, and 4. Detailed studies on soils. Soil Sci. 87: 13-21, 87: 83-88, 93: 113-123, and 96: 112-120.

Fisher, R. A. and Thomas, R. P. 1935. The determination of the forms of inorganic phosphorus in soils. J. Amer. Soc. Agron. 27: 863-873.

Fraps, G. S. 1906. Availability of the phosphoric acid of the soil. J. Amer. Chem. Soc. 28: 823-834.

Ghani, M. O. 1943. Fractionation of soil phosphorus. 1. Method of extraction. Abstr. in Soils Fert. 6: 181.

Ghobadian, A. 1967. Fixation and release of phosphorus forms in saline and steppe soils of Austria. Abstr. in Soils Fert. 30: 2432.

Grigg, J. L. 1965. Inorganic phosphorus fractions in South Island soils and their solubility in commonly used extracting solutions. N.Z. J. Agr. Res. 8: 313-326.

Haas, P. 1964. Study on different forms of inorganic phosphates in soils of Hungary. 8th Int. Cong. Soil Sci. 4: 487-494.

Halstead, R. L. 1967. Chemical availability of native and applied phosphorus in soils and their textural fractions. Soil Sci. Soc. Amer. Proc. 31: 414-419.

Hanley, P. K. and Murphy, M. D. 1970. Phosphate forms in particle size separates of Irish soils in relation to drainage and parent materials. Soil Sci. Soc. Amer. Proc. 34: 587-590.

Hawkins, R. H. and Kunze, G. W. 1965. Phosphate fractions in some Texas Grumusols and their relation to soil weathering and available phosphorus. Soil Sci. Soc. Amer. Proc. 29: 650-656.

Hsu, P. H. and Jackson, M. L. 1960. Inorganic phosphate transformations by chemical weathering in soils as influenced by pH. Soil Sci. 90: 16-24.

Jones, R. K. and Crack, B. J. 1970. Studies on some Solodic soils in northeastern Queensland. 2. Glasshouse assessment of plant nutrient status. Aust. J. Exptl. Agr. Animal Husb. 10: 342-349.

Juo, A. S. R. and Ellis, B. G. 1968a. Particle size distribution of aluminum, iron and calcium phosphates in soil profiles. Soil Sci. 106: 374-380.

Juo, A. S. R. and Ellis, B. G. 1968b. Chemical and physical properties of iron and aluminum phosphates and their relation to phosphorus availability. Soil Sci. Soc. Amer. Proc. 32: 216-221.

Kaila, A. 1965. Some phosphorus test values and fractions of inorganic phosphorus in soils. J. Sci. Agr. Soc. Finland 37: 175-185.

Khan, S. U. and Webster, G. R. 1966. Certain equilibrium ion ratios for a Solonetzic soil. J. Soil Sci. 17: 248-254.

Khanna, P. K. 1967. Inorganic soil phosphate fractions as related to soil-test values by common methods. Plant Soil 26: 277-284.

Khin, A. and Leeper, G. W. 1960. Modifications in Chang and Jackson's procedure for fractionating soil phosphorus. Agrochimica 4: 246-254.

Kurtz, L. T. and Quirk, J. P. 1965. Phosphate adsorption and phosphate fractions in field soils of varying histories of phosphate fertilization. Aust. J. Agr. Res. 16: 403-412.

Kvachi, K. P. and Panov, N. P. 1969. Comparative characteristics of available elements in soils of Solonetz complexes along the Volga River. Abstr. in Chem. Abstr. 73: 86953.

Levesque, M. 1967. The effect of soil temperature on native and added phosphorus in some northern Ontario soils. Can. J. Soil Sci. 47: 123-129.

Machold, O. 1963. The bond of 'labile' phosphate in soil. Z. Pfl. Dung Bodenk. 103: 132-138.

MacKenzie, A. F. 1962. Inorganic soil phosphorus fractions of some Ontario soils as studied using isotopic exchange and solubility criteria. Can. J. Soil Sci. 42: 150-156.

Martens, D. C., Lutz, J. A., and Jones, G. D. 1969. Form and availability of phosphorus in selected Virginia soils as related to available phosphorus tests. Agron. J. 61: 616-621.

Mathieu, A. L. 1960. The mineralogy of the clay fraction in relation to the genesis of Solodized Solonetz soils. Ph. D. Thesis, Univ. of Saskatchewan, Saskatoon.

McKeague, J. A. and Day, J. H. 1966. Dithionite- and oxalate-extractable iron and aluminum as aids in differentiating various classes of soils. Can. J. Soil Sci. 46: 13-22.

Mikanaev, T. D. 1968. Level and composition of phosphates in Solonetzes of the Tselinograd Oblast. Abstr. in Chem. Abstr. 72: 30640.

Miller, J. R. and Axley, J. H. 1956. Correlation of chemical soil tests for available phosphorus with crop response, including a proposed method. Soil Sci. 82: 117-127.

Odynsky, Wm. 1945. Solonetz soils in Alberta. Sci. Agr. 25: 780-790.

Odynsky, Wm., Lindsay, J. D., Reeder, S. W., and Wynnyk, A. 1961. "Reconnaissance Soil Survey of the Beaverlodge and Blueberry Mountain Sheets." Univ. of Alberta Bull. No. SS-3.

Odynsky, Wm., Wynnyk, A., and Newton, J. D. 1956. "Reconnaissance Soil Survey of the Grande Prairie and Sturgeon Lake Sheet." Univ. of Alberta Bull. No. 60.

Olsen, S. R., Cole, C. V., Watanabe, F. S., and Dean, L. A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Dept. Agr. Circ. 939.

Omanwar, P. K. 1970. Available phosphorus in relation to the physical and chemical characteristics of phosphorus of some Alberta soils. Ph. D. Thesis, Univ. of Alberta, Edmonton.

Pawluk, S. 1967. Soil analyses by atomic absorption spectrophotometry. At. Absorption Newsletter 6: 53-56.

Pawluk, S. and Dumanski, J. 1969. Evolution of Solonetzic soils. In "Pedology and Quaternary Research" p. 197-199. Pawluk, S. (ed). Pub. Alberta Institute of Pedology, Edmonton.

Payne, H. and Hanna, W. J. 1965. Correlations among soil phosphorus

fractions, extractable phosphorus and plant content of phosphorus.

J. Agr. Food Chem. 13: 322-326.

Peech, M. 1965. Hydrogen-ion activity. In "Methods of Soil Analysis"

p. 914-926. Pub. Amer. Soc. Agron. Wisconsin, USA.

Peters, T. W. and Bowser, W. E. 1960. "Soil Survey of the Rocky

Mountain House Sheet." Univ. of Alberta Bull. No. SS-1.

Peterson, G. W. and Corey, R. B. 1966. A modified Chang and Jackson

procedure for routine fractionation of inorganic soil phosphates.

Soil Sci. Soc. Amer. Proc. 30: 563-565.

Pratt, P. F. and Garber, M. J. 1964. Correlations of phosphorus avail-

ability by chemical tests with inorganic phosphorus fractions.

Soil Sci. Soc. Amer. Proc. 28: 23-26.

Rajendran, N. and Sutton, C. D. 1970. Re-sorption of soil phosphate

during fractionation. J. Soil Sci. 21: 199-202.

Riecken, F. F. 1943. Some considerations in the magnesium cycle of

weathering in Solonetz soils. Soil Sci. Soc. Amer. Proc. 8: 391-395.

Robertson, J. A. 1962. Comparison of an acid and alkaline extracting

solution for measuring available phosphorus in Alberta soils.

Can. J. Soil Sci. 42: 115-121.

Rost, C. O. and Maehl, K. A. 1943. Some Solodized soils of the Red

River Valley. Soil Sci. 55: 301-312.

Rotini, O. T. and El-Nennah, M. 1971. Evaluation of the relative

availability of inorganic phosphorus fractions in some Italian

soils using isotopic exchange and solubility criteria. Agrochimica

16: 23-32.

Saunders, W. M. H. 1959. Effect of phosphate top dressing on a soil from andesitic volcanic ash. 1. Forms of soil phosphorus and a method for their determination. N.Z. J. Agr. Res. 2: 427-444.

Saunders, W. M. H. and Williams, E. G. 1955. Observations on the determination of total organic phosphorus in soils. J. Soil Sci. 6: 254-267.

Scheelar, M. D. and Odynsky, Wm. 1968. "Reconnaissance Soil Survey of the Grimshaw and Notikewin Area." Univ. of Alberta Bull. No. SS-8.

Schwertmann, U. 1964. The differentiation of iron oxide in soils by a photochemical extraction with acid ammonium oxalate. Z. Pfl. Dung Bodenk. 105: 194-201.

Singh, R. N., Martens, D. C., and Obenshain, S. S. 1966. Plant availability and form of residual phosphorus in Davidson clay loam. Soil Sci. Soc. Amer. Proc. 30: 617-620.

Smeck, N. E. and Runge, E. C. A. 1971. Phosphorus availability and redistribution in relation to profile development in an Illinois landscape segment. Soil Sci. Soc. Amer. Proc. 35: 952-959.

Smith, A. N. 1965a. Distinction between iron and aluminum phosphate in Chang and Jackson's procedure for fractionating inorganic soil phosphorus. Agrochimica 9: 162-168.

Smith, A. N. 1965b. The supply of soluble phosphorus to the wheat plant from inorganic soil phosphorus. Plant Soil 22: 314-316.

Smith, A. N. 1972. Corrections for resorption of phosphate during the extraction of aluminum-bound soil phosphate. Soil Sci. 113: 55-56.

Susuki, A., Lawton, K., and Doll, E. C. 1963. Phosphorus uptake and soil tests as related to forms of phosphorus in some Michigan soils. Soil Sci. Soc. Amer. Proc. 27:.401-403.

Syers, J. K., Smillie, G. W., and Williams, J. D. H. 1972. Calcium fluoride formation during extraction of calcareous soils with fluoride. 1. Implications to inorganic phosphorus fractionation schemes. Soil Sci. Soc. Amer. Proc. 36: 20-25.

Syers, J. K., Williams, J. D. H., Tyner, E. H., and Walker, T. W. 1969. Primary and secondary origin of "nonextractable" soil inorganic phosphorus. Soil Sci. Soc. Amer. Proc. 33: 635-636.

Syers, J. K., Williams, J. D. H., and Walker, T. W. 1970. Mineralogy and forms of inorganic phosphorus in a Graywacke soil-rock weathering sequence. Soil Sci. 110: 100-106.

Szabolcs, I. (ed). 1971. "European Solonetz soils and their reclamation." Pub. Akademiai Kiado, Budapest, Hungary.

Tandon, H. L. S. and Kurtz, L. T. 1968. Isotopic exchange characteristics of aluminum- and iron-bound fractions of soil phosphorus. Soil Sci. Soc. Amer. Proc. 32: 799-802.

Taylor, A. W., Gurney, E. L., and Lindsay, W. L. 1960. An evaluation of some iron and aluminum phosphates as sources of phosphate for plants. Soil Sci. 90: 25-31.

Taylor, A. W., Lindsay, W. L., Huffman, E. O., and Gurney, E. L. 1963. Potassium and ammonium taranakites, amorphous aluminum phosphate, and variscite as sources of phosphate for plants. Soil Sci. Soc. Amer. Proc. 27: 148-151.

Tripathi, B. R., Tandon, H. L. S., and Tyner, E. H. 1970. Native
     inorganic phosphorus forms and their relation to some chemical
     indices of phosphate availability for soils of Agra District,
     India. Soil Sci. 109: 93-101.

Tyner, E. H. and Davide, J. G. 1962. Some criteria for evaluating
     soil phosphorus tests for lowland rice soils. In "Transactions
     of Joint Meeting of Comm. IV and V" p. 625-634. Neale, G. J. (ed).
     Pub. Int. Soc. Soil Sci.

Walker, T. W. 1965. The significance of phosphorus in pedogenesis.
     In "Experimental Pedology" p. 295-316. Hallsworth, E. G. and
     Crawford, D. V. (ed). Pub. Butterworths, London.

Warren, R. G. and Cooke, G. W. 1965. Comparisons between methods of
     measuring soluble phosphorus and potassium in soils used for
     fertilizer experiments on sugarbeet. In "Soil Phosphorus" p. 75-
     83. Tech. Bull. 13, Min. Agr. Fish and Food. Pub. HMSO, London.

Weir, C. C. and Soper, R. J. 1962. Adsorption and exchange studies
     of phosphorus in some Manitoba soils. Can. J. Soil Sci. 42: 31-42.

Westin, F. C. and Buntley, G. J. 1967. Soil phosphorus in South
     Dakota. 3. Phosphorus fractions in some Borolls and Ustolls.
     Soil Sci. Soc. Amer. Proc. 31: 521-528.

Westin, F. C. and DeBrito, J. G. 1969. Phosphorus fractions of some
     Venezuelan soils as related to their stage of weathering. Soil
     Sci. 107: 194-202.

Williams, C. H. 1950. Studies on soil phosphorus. 1. A method for
     the partial fractionation of soil phosphorus. J. Agr. Sci. 40:
     233-242.

Williams, R. 1937. The solubility of soil phosphorus and other compounds in sodium hydroxide solutions. J. Agr. Sci. 27: 259-270.

Williams, J. D. H., Syers, J. K., and Walker, T. W. 1967. Fractionation of soil inorganic phosphate by a modification of Chang and Jackson's procedure. Soil Sci. Soc. Amer. Proc. 31: 736-739.

Williams, J. D. H. and Walker, T. W. 1969. Fractionation of phosphate in a maturity sequence of New Zealand basaltic soil profiles. 1 and 2. Soil Sci. 107: 22-30 and 213-219.

Wynnyk, A. 1950. Base exchange studies of some Solonetzic soils of the Peace River District. M. Sc. Thesis, Univ. of Alberta, Edmonton.

Wynnyk, A., Lindsay, J. D., and Odynsky, Wm. 1969. "Soil Survey of the Whitecourt and Barrhead Area." Univ. of Alberta Bull. No. SS-10.

VIII. APPENDIX

Table A1   Physical and chemical properties of the Maleb – Hemaruka – Halliday (Mb – Hu – Hd) sequence

Horizon	Depth cm	pH in 0.01 M CaCl$_2$	Oxalate extractable Al %	Fe %	Organic C %	Particle-size separates Sand %	Silt %	Clay %	Al-P ppm	Fe-P ppm	Ca-P ppm	Occl-P ppm	Organic P ppm	Residual P ppm	Total P ppm
MALEB															
Profile 1															
Ah	0- 10	6.6	.11	.16	2.4	45	33	22	25	41	132	50	266	51	565
Ba	10- 38	6.1	.10	.15	0.9	49	25	26	8	20	142	32	162	64	428
Cca	38- 79	7.4	.06	.10	0.5	35	24	41	7	1	356	24	74	73	535
Ck	79-112	7.7	.04	.17	0.2	39	22	39	5	tr	403	30	44	39	521
Profile 2															
Ah	0- 18	6.2	.11	.16	3.9	37	39	24	12	21	96	28	407	91	655
Ba	18- 48	6.4	.12	.14	1.0	35	32	33	8	18	123	15	188	84	436
Cca	48- 99	7.3	.05	.11	0.4	37	23	40	9	2	371	15	74	83	554
Ck	99-114	7.8	.04	.17	0.2	39	25	36	12	1	352	31	52	99	547
Profile 3															
Ah	0- 19	6.4	.13	.20	4.1	32	43	25	19	28	128	57	402	51	685
Ba	19- 46	6.0	.16	.26	1.3	22	37	41	9	26	244	35	275	64	653
Cca	46- 76	7.4	.06	.13	0.6	28	25	47	8	1	378	16	134	19	556
Ck	76-102	7.7	.04	.18	0.3	35	24	41	9	1	397	13	39	81	540
HEMARUKA															
Profile 1															
Ah	0- 8	4.2	.16	.27	5.8	43	31	26	17	62	16	39	702	109	945
Ae	8- 12	4.9	.10	.26	2.1	40	33	27	8	35	56	36	381	60	576
Bat1	12- 24	6.6	.13	.25	1.6	31	27	42	10	22	158	53	227	50	520
Bat2	24- 37	7.8	.09	.25	1.0	34	25	41	8	10	321	27	121	47	534
Csk	62-122	7.9	.06	.28	0.5	36	23	41	10	10	361	40	48	42	511
Profile 2															
Ah	0- 8	4.4	.24	.48	10.6	28	45	27	28	113	13	20	962	58	1,194
Acgj	8- 12	4.7	.09	.28	2.1	31	41	28	8	40	14	18	234	86	400
Batgj1	12- 20	6.1	.15	.48	1.4	26	31	43	8	27	32	24	185	83	359
Batgj2	20- 33	6.9	.12	.33	0.7	33	30	37	4	12	168	12	92	62	350
Cskgj	62-122	7.7	.06	.19	0.4	37	25	38	2	tr	397	29	63	40	531
Profile 3															
Ah	0- 9	5.5	.15	.28	6.4	40	39	21	22	52	23	47	865	50	1,059
Ae	13- 15	4.5	.13	.31	2.0	41	33	26	12	44	24	54	473	58	665
Bat1	15- 30	5.6	.17	.27	1.4	38	16	46	6	23	52	37	270	52	440
Bat2	30- 43	7.4	.11	.25	0.8	42	20	38	5	17	219	36	138	28	443
Csk	64-102	7.7	.04	.22	0.3	47	17	36	7	tr	327	17	30	33	414
HALLIDAY															
Profile 1															
Ah	0- 10	5.3	.11	.18	3.7	46	32	22	22	66	115	53	424	50	730
Ae	15- 23	7.3	.04	.10	0.9	50	33	17	9	17	95	39	123	62	345
Bat	28- 41	7.5	.09	.13	0.7	47	25	28	19	16	160	59	139	56	449
Btsk	41- 56	7.6	.07	.14	0.5	51	23	26	42	43	159	60	110	75	489
Csaca	107-132	7.9	.04	.23	0.3	41	24	35	43	1	404	63	31	142	684
Profile 2															
Ah	0- 8	5.6	.14	.23	4.2	36	39	25	28	58	84	57	405	34	666
Ae	13- 18	4.6	.16	.12	1.6	47	27	26	17	31	16	28	316	63	471
Bat	23- 36	7.4	.11	.23	1.6	38	21	41	6	2	248	26	160	82	524
Btsk	36- 66	7.7	.04	.21	1.2	41	24	35	8	1	296	41	74	64	484
Csaca	107-122	7.3	.10	.39	0.5	10	31	59	7	tr	372	20	27	163	589
Profile 3															
Ah	0- 20	4.5	.22	.38	3.8	40	33	27	42	86	27	30	678	84	947
Ae	30- 40	6.0	.05	.31	0.9	31	39	30	7	21	66	40	96	102	332
Bat	44- 64	7.5	.21	.45	0.9	26	27	47	8	16	114	31	122	76	367
Btsk	64- 82	8.3	.07	.25	0.8	32	25	43	16	5	267	33	50	80	451
Csk	127-135	7.7	.05	.24	0.7	34	22	44	6	4	325	35	29	71	470

Table A2   Physical and chemical properties of the Beaverhills - Camrose - Daysland (Bh - Cam - Dl) sequence

Horizon	Depth cm	pH in 0.01 M CaCl$_2$	Oxalate extractable Al %	Fe %	Organic C %	Particle-size separates Sand %	Silt %	Clay %	Al-P ppm	Fe-P ppm	Ca-P ppm	Occl-P ppm	Organic P ppm	Residual P ppm	Total P ppm
BEAVERHILLS															
Profile 1															
Ah	0- 25	5.3	.15	.17	5.5	35	24	31	15	36	62	39	610	48	810
Bm	35- 65	5.6	.09	.18	1.0	30	29	41	6	25	123	30	99	75	358
Ck	75-100	7.3	.03	.19	0.5	45	25	30	3	1	315	18	51	70	458
Profile 2															
Ah	0- 25	5.4	.15	.21	3.6	36	27	37	20	56	108	78	445	67	774
Bm	25- 70	5.6	.10	.19	0.8	35	26	39	7	26	172	54	135	47	441
Ck	70-100	7.3	.04	.21	0.6	36	27	37	3	3	333	30	42	89	500
Profile 3															
Ah	0- 15	6.3	.15	.14	4.3	42	29	29	25	43	80	50	511	72	781
Bm	15- 45	6.3	.11	.11	0.7	43	22	35	8	21	73	44	103	46	295
Ck	45-100	7.4	.04	.17	0.7	47	23	30	6	1	273	29	56	62	427
CAMROSE															
Profile 1															
Ah	0- 15	4.7	.28	.39	4.3	38	35	27	8	27	30	36	792	89	982
Bnt1	29- 39	6.9	.17	.32	0.9	27	39	34	2	18	92	52	170	86	420
Bnt2	39- 49	7.5	.12	.36	0.5	41	26	33	2	21	129	45	118	67	382
Csaca	49- 80	8.1	.04	.23	0.4	31	28	41	6	tr	402	15	73	49	545
Profile 2															
Ah	0- 10	4.7	.33	.47	8.5	25	46	29	51	123	26	85	1,334	64	1,683
Bnt1	12- 22	6.3	.32	.42	1.9	15	37	48	12	31	39	54	193	84	413
Bnt2	22- 27	7.0	.26	.36	1.4	13	38	49	12	24	54	71	137	48	346
Csaca	32- 70	8.0	.10	.36	0.3	34	23	43	8	26	290	72	65	17	478
Profile 3															
Ah	0- 10	4.5	.26	.47	10.8	27	52	21	27	90	10	58	1,420	130	1,735
Bnt1	14- 20	6.2	.26	.50	2.0	23	29	48	4	35	107	60	376	77	659
Bnt2	20- 30	7.8	.21	.41	1.5	24	22	54	3	21	127	58	258	78	545
Csaca	40- 70	8.4	.06	.33	0.5	22	29	49	6	2	464	45	64	71	652
DAYSLAND															
Profile 1															
Ah	0- 15	5.2	.15	.31	5.7	41	37	22	18	42	60	76	813	55	1,064
Ae	25- 30	4.9	.11	.19	1.1	58	24	18	24	46	43	62	268	53	496
Bnt1	35- 45	6.6	.11	.28	1.0	37	37	26	8	24	110	76	191	46	455
Bnt2	45- 55	7.4	.10	.32	0.5	52	24	24	6	23	159	71	96	47	402
Csak	65- 95	8.4	.06	.29	0.3	32	27	41	16	tr	422	83	40	75	636
Profile 2															
Ah	0- 15	5.1	.19	.24	5.7	44	35	21	24	38	38	30	735	48	913
Ae	15- 25	4.8	.10	.17	0.8	56	24	20	7	25	53	30	190	114	419
Bnt1	28- 43	5.5	.12	.21	0.9	40	22	38	6	36	76	52	188	96	454
Bnt2	43- 63	6.8	.10	.23	0.6	38	23	39	3	25	127	44	98	97	394
Csak	90-100	7.7	.05	.23	0.5	36	25	39	1	tr	366	16	19	159	561
Profile 3															
Ah	0- 10	5.2	.15	.30	7.2	38	41	21	22	52	35	52	992	34	1,187
Ae	10- 20	4.5	.15	.19	1.3	45	33	22	10	31	27	55	276	66	465
Bnt1	25- 35	6.3	.16	.28	1.0	36	25	39	3	28	73	60	158	55	377
Bnt2	35- 45	6.9	.13	.25	0.8	38	25	37	1	25	110	64	122	54	376
Ck	60- 90	7.6	.06	.22	0.3	43	29	28	4	26	354	55	50	67	556

Table A3   Physical and chemical properties of the Cooking Lake - Dnister - Nakamun (Ck - Dn - Nk) sequence

Horizon	Depth cm	pH in 0.01 M CaCl$_2$	Oxalate extractable Al %	Fe %	Organic C %	Particle-size separates Sand %	Silt %	Clay %	Al-P ppm	Fe-P ppm	Ca-P ppm	Gccl-P ppm	Organic P ppm	Residual P ppm	Total P ppm
COOKING LAKE															
Profile 1															
Ae	2- 15	6.2	.08	.20	0.6	47	30	23	20	52	21	70	116	31	310
Bt1	25- 50	5.0	.15	.35	0.4	36	20	44	2	22	15	44	98	46	227
Bt2	50- 95	4.7	.15	.54	0.5	21	31	48	6	63	54	64	102	33	322
Ck	145-160	7.2	.05	.10	0.3	38	25	37	3	1	356	53	47	70	530
Profile 2															
Ae	2- 12	4.8	.05	.13	0.5	46	32	22	6	24	15	31	122	56	254
Bt1	20- 40	4.2	.16	.21	0.5	36	21	43	3	26	9	54	117	63	272
Bt2	40- 90	4.2	.14	.23	0.4	34	23	43	6	46	33	63	113	37	298
Ck	130-150	7.0	.05	.16	0.3	38	23	39	3	3	345	34	49	100	534
Profile 3															
Ae	5- 20	5.6	.04	.08	0.5	46	34	20	21	46	56	38	86	26	273
Bt1	27- 50	5.0	.14	.17	0.6	34	25	41	2	35	50	50	122	19	278
Bt2	50- 80	5.0	.13	.22	0.5	35	22	43	2	38	88	65	102	23	318
Ck	115-150	7.0	.05	.16	0.3	41	22	37	1	4	363	46	52	44	510
DNISTER															
Profile 1															
Ae	2- 15	4.4	.08	.14	0.4	58	24	18	16	33	20	24	112	87	292
Bnt1	15- 28	6.0	.15	.28	0.5	31	28	41	6	22	68	65	113	51	325
Bnt2	28- 64	6.9	.13	.33	0.6	30	23	47	4	28	209	57	98	40	436
Ck	86- 96	7.5	.06	.27	0.5	30	25	45	3	2	366	28	57	88	544
Profile 2															
Ae	4- 8	4.3	.16	.48	1.4	35	35	30	3	45	45	52	232	34	411
Bnt1	8- 28	4.6	.25	.50	1.2	30	24	46	2	52	119	53	228	41	495
Bnt2	28- 51	7.2	.06	.33	0.8	30	25	45	10	4	424	35	88	53	614
Ck	81- 91	7.4	.08	.08	0.2	20	32	48	11	3	366	9	22	60	471
Profile 3															
Ae	5- 16	4.2	.18	.44	0.6	25	55	20	12	67	104	41	84	60	368
Bnt1	16- 27	4.4	.23	.40	0.7	28	35	37	6	35	94	41	157	42	375
Bnt2	27- 58	5.4	.19	.30	0.7	36	23	41	7	29	177	43	131	49	436
Csaca	58-117	7.6	.05	.20	0.3	37	24	39	3	1	412	48	49	26	539
NAKAMUN															
Profile 1															
Ae	4- 20	4.1	.10	.24	0.2	42	42	16	7	36	40	47	66	22	218
Bnt1	28- 46	4.1	.23	.49	0.6	28	22	50	12	86	53	65	113	33	362
Bnt2	46- 64	4.4	.19	.41	0.6	30	22	48	11	73	130	39	106	62	421
Ck	102-122	7.1	.06	.29	0.5	33	24	43	6	8	369	28	55	48	514
Profile 2															
Ae	5- 13	4.2	.11	.41	0.9	34	44	22	17	82	69	66	133	63	430
Bnt1	21- 34	5.5	.16	.36	0.5	28	23	49	9	48	85	88	119	32	381
Bnt2	34- 46	6.8	.10	.30	0.4	36	23	41	6	36	140	73	85	32	372
Csaca	46-122	7.6	.05	.23	0.3	35	24	41	2	1	378	35	24	87	527
Profile 3															
Ae	5- 15	4.8	.05	.23	0.4	26	56	18	4	31	116	33	88	58	330
Bnt1	18- 25	6.2	.21	.37	0.8	29	31	40	12	45	226	47	178	57	565
Bnt2	25- 41	7.3	.11	.21	0.5	37	24	39	3	9	318	45	119	49	543
Csak	81-117	7.7	.05	.24	0.3	39	24	37	2	3	398	47	35	68	553

Table A4   Physical and chemical properties of the Ap horizons used for the greenhouse experiment

Sample no	pH in 0.01 M CaCl₂	Oxalate extractable Al %	Oxalate extractable Fe %	Organic C %	Particle-size separates Sand %	Particle-size separates Silt %	Particle-size separates Clay %	Al-P ppm	Fe-P ppm	Ca-P ppm	Occl-P ppm	Organic P ppm	Residual P ppm	Total P ppm
						CHERNOZEMIC HORIZONS								
1	5.6	.14	.27	6.6	29	38	33	26	66	90	77	698	49	1,006
2	5.6	.14	.24	4.9	20	43	37	34	72	50	79	531	51	817
3	5.2	.17	.36	5.8	21	39	40	21	66	67	83	777	53	1,067
4	5.8	.12	.23	5.8	33	36	31	35	70	96	87	694	40	1,022
5	5.5	.16	.49	6.6	27	40	33	14	55	68	60	742	68	1,007
6	5.8	.11	.22	3.0	47	27	26	34	71	103	89	381	22	700
7	5.4	.15	.36	6.4	25	33	42	32	74	49	69	733	64	1,021
8	5.4	.21	.51	6.6	21	41	38	21	66	75	63	904	13	1,142
9	5.8	.16	.26	6.4	33	34	33	30	63	82	108	748	18	1,049
10	5.2	.18	.23	5.9	51	23	26	43	59	86	67	678	57	990
						SOLONETZIC HORIZONS								
1	4.8	.22	.49	5.1	35	34	31	52	141	36	97	743	77	1,146
2	4.6	.19	.44	5.1	41	30	29	20	68	34	62	724	97	1,005
3	4.8	.21	.46	5.6	26	43	31	21	66	26	74	662	53	902
4	4.6	.18	.37	5.1	35	38	27	60	97	39	81	720	73	1,070
5	4.6	.19	.46	5.0	33	36	31	58	144	46	74	753	83	1,158
6	4.8	.18	.47	4.1	39	32	29	45	136	36	82	702	55	1,056
7	4.5	.22	.43	5.4	34	33	33	65	120	33	104	784	85	1,191
8	4.5	.18	.41	4.4	39	32	29	66	140	38	110	769	75	1,198
9	4.6	.23	.49	5.3	24	41	35	75	142	34	93	806	104	1,254
10	4.6	.16	.41	3.8	41	37	22	59	117	23	78	650	88	1,015

Table A5   Legal locations of the Ap horizon samples from the
            Tofield - Ryley area

Sample no*	Solonetzic sample	Chernozemic sample
1	NE 27-49-17-W4	SE 31-50-19-W4
2	NW 26-49-17-W4	SE 31-50-19-W4
3	NE 14-49-17-W4	NW 19-50-19-W4
4	SW 23-49-17-W4	NE 36-50-20-W4
5	SW 23-49-17-W4	NE 30-50-19-W4
6	NW 24-49-17-W4	NE 30-50-19-W4
7	SH 25-49-17-W4	NE 31-50-19-W4
8	NW 24-49-17-W4	NE 31-50-19-W4
9	NW 24-49-17-W4	NE 31-50-19-W4
10	NW 24-49-17-W4	NE 29-50-19-W4
11	NW 10-50-17-W4	NE 29-50-19-W4
12	EH 09-50-17-W4	NW 29-50-19-W4
13	EH 09-50-17-W4	SW 21-50-19-W4
14	NW 27-50-17-W4	SW 17-50-16-W4
15	SE 28-50-17-W4	NE 18-50-16-W4
16	SE 25-50-17-W4	NW 30-50-19-W4
17	NE 24-50-17-W4	NW 30-50-19-W4

* The samples are not paired.

Table A6   Legal locations of the virgin soil profiles

Soil series	Profile 1	Profile 2	Profile 3
Maleb, Mb	NE 16-26-04-W4	SE 20-28-03-W4	NW 23-25-06-W4
Hemaruka, Hu	SW 27-27-10-W4	NW 04-33-13-W4	NW 24-33-11-W4
Halliday, Hd	SW 27-27-10-W4	NW 04-33-13-W4	SE 27-36-14-W4
Beaverhills, Bh	NE 19-48-21-W4	SE 26-48-21-W4	NE 31-48-20-W4
Camrose, Cam	NE 19-50-18-W4	SE 23-49-18-W4	NE 32-49-18-W4
Daysland, Dl	NW 11-45-16-W4	SE 29-44-15-W4	NW 31-44-15-W4
Cooking Lake, Ck	SW 13-51-22-W4	NE 35-50-22-W4	SW 34-51-22-W4
Dnister, Dn	NW 35-56-02-W5	SW 30-57-02-W5	NW 34-59-27-W4
Nakamun, Nk	SW 05-57-01-W5	SW 16-59-26-W4	SW 34-59-27-W4

Table A7   Legal locations of the Ap horizon samples used for
            the greenhouse experiment

Sample no*	Solonetzic sample	Chernozemic sample
1	NE 27-49-17-W4	SE 31-50-19-W4
2	NW 26-49-17-W4	NE 36-50-20-W4
3	NE 14-49-17-W4	NE 30-50-19-W4
4	SW 23-49-17-W4	NE 31-50-19-W4
5	NW 24-49-17-W4	NE 29-50-19-W4
6	EH 09-50-17-W4	SW 17-50-16-W4
7	SE 25-50-17-W4	NW 30-50-19-W4
8	NE 24-50-17-W4	NE 24-51-25-W4***
9	SE 18-39-18-W4**	SE 11-54-22-W4***
10	NW 15-47-17-W4**	SE 24-40-27-W4***

*   The samples are not paired.

**   Samples from the Camrose - Stettler area.

*** Samples from the Edmonton - Lacombe area, used in a previous
     investigation (Omanwar, 1970).

Table A8   Sorption of added phosphorus during NH_4Cl and
              NH_4F extractions*

Sample no	24.9 ug P/50 ml of NH_4Cl extract		37.3 ug P/50 ml of NH_4F extract	
	Proportion of sorbed P	Correction factor	Proportion of sorbed P	Correction factor
	SOLONETZIC SAMPLES			
1	.16	1.19	-.01	0.99
2	.50	2.00	.12	1.14
3	.41	1.69	.14	1.16
9	-.12	0.89	-.02	0.98
	CHERNOZEMIC SAMPLES			
3	.15	1.18	.05	1.05
5	.35	1.54	.18	1.22
8	.42	1.72	.16	1.19
9	-.17	0.85	.09	1.10

* Method as outlined by Smith (1965a) except that one phosphorus
  standard was used.

Table A9   Dry matter yield of barley

Sample no	ppm P applied	Yield, g/pot Replicates		
		1	2	3
SOLONETZIC SAMPLES				
1	0	2.02	2.07	1.93
	20	2.10	2.25	2.35
	40	2.32	2.26	2.26
2	0	0.87	1.21	1.17
	20	1.86	1.96	2.01
	40	2.38	2.42	2.17
3	0	1.10	1.14	1.04
	20	1.91	1.99	1.83
	40	2.34	2.04	2.10
4	0	1.86	2.18	2.07
	20	2.22	2.46	2.23
	40	2.02	2.12	2.05
5	0	1.68	1.64	1.76
	20	1.87	2.24	2.18
	40	2.42	2.42	2.08
6	0	1.30	1.24	1.40
	20	1.78	1.62	1.57
	40	1.82	1.74	1.85

Table A9   (Continued)

Sample no	ppm P applied	Yield, g/pot Replicates		
		1	2	3
7	0	1.21	1.57	1.43
	20	1.53	1.85	1.66
	40	1.80	1.89	2.04
8	0	1.72	2.06	1.88
	20	1.66	2.27	2.20
	40	2.06	2.28	2.07
9	0	2.08	2.26	2.39
	20	2.59	2.63	2.82
	40	2.66	2.94	2.36
10	0	1.93	2.04	1.78
	20	2.25	2.40	2.04
	40	2.44	2.30	2.50

CHERNOZEMIC SAMPLES

1	0	2.35	2.38	2.54
	20	2.63	2.92	3.13
	40	3.31	3.29	3.18
2	0	1.66	1.77	1.76
	20	2.15	2.34	2.03
	40	2.46	2.28	2.08
3	0	2.22	2.41	2.11
	20	3.22	3.11	2.83
	40	3.59	3.07	2.97

Table A9   (Continued)

Sample no	ppm P applied	Yield, g/pot Replicates		
		1	2	3
4	0	2.12	2.46	2.43
	20	2.68	2.76	2.53
	40	2.75	2.88	2.81
5	0	0.84	0.86	0.80
	20	1.80	1.92	2.00
	40	2.32	2.21	2.50
6	0	1.65	1.82	1.60
	20	2.07	2.23	2.02
	40	2.50	2.60	2.45
7	0	1.86	2.23	2.10
	20	2.37	2.46	2.34
	40	2.72	2.76	2.73
8	0	0.73	0.78	0.58
	20	1.22	1.05	1.10
	40	1.86	1.56	1.77
9	0	1.75	1.71	1.82
	20	2.68	2.59	2.63
	40	2.89	2.62	2.64
10	0	2.65	2.73	2.33
	20	3.25	3.29	3.06
	40	3.00	3.17	2.97

Table A10   Per cent nitrogen in the plant tissue and uptake
of nitrogen by barley

Sample no	% N ppm P applied		mg N/pot ppm P applied	
	0	40	0	40
SOLONETZIC SAMPLES				
1	3.96	3.58	80	82
2	5.77	3.84	62	89
3	5.72	4.06	62	88
4	4.76	3.66	97	75
5	5.10	5.11	86	118
6	4.94	3.71	65	67
7	4.50	4.20	63	80
8	5.12	4.45	97	95
9	5.12	4.42	115	117
10	4.83	4.02	93	97
Mean ± s.d.	4.98 ± .53	4.10 ± .47	82 ± 19	91 ± 17
CHERNOZEMIC SAMPLES				
1	4.00	3.18	97	104
2	5.00	3.88	86	88
3	4.28	3.64	96	117
4	4.06	3.30	95	93
5	6.26	3.40	52	80
6	4.33	3.22	73	81
7	4.62	3.32	95	91
8	5.62	2.88	39	50
9	5.84	4.40	103	120
10	3.91	3.78	100	115
Mean ± s.d.	4.79 ± .85	3.50 ± .43	84 ± 22	94 ± 21

Table A11   Per cent phosphorus in the plant tissue and uptake
of phosphorus by barley

	% P ppm P applied		mg P/pot ppm P applied	
Sample no	0	40	0	40
SOLONETZIC SAMPLES				
1	.25	.38	5.1	8.6
2	.20	.29	2.1	6.8
3	.25	.25	2.8	5.5
4	.27	.45	5.5	9.3
5	.20	.29	3.4	6.7
6	.26	.34	3.5	6.0
7	.21	.37	2.9	7.0
8	.28	.36	5.2	7.7
9	.26	.36	5.7	9.4
10	.24	.36	4.5	8.7
Mean ± s.d.	.24 ± .03	.34 ± .06	4.1 ± 1.3	7.6 ± 1.4
CHERNOZEMIC SAMPLES				
1	.25	.49	6.1	16
2	.26	.44	4.6	10
3	.18	.46	4.2	15
4	.31	.49	7.3	14
5	.22	.33	1.8	7.7
6	.23	.48	3.8	12
7	.23	.43	4.7	12
8	.14	.28	1.0	4.9
9	.20	.42	3.6	11
10	.26	.53	6.6	16
Mean ± s.d.	.23 ± .05	.44 ± .08	4.4 ± 2.0	12 ± 3.6

END OF REEL

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