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Forms and cycling of phosphorus in prairie and boreal forest soils

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Abstract. The distribution of soil P among inorganic and organic forms was examined in prairie and boreal forest soil profiles from Saskatchewan, Canada. A sequential extraction procedure was employed to separate P into labile and stable inorganic (P_i) and organic (P_o) fractions. Profile depth, climate, vegetation, and cultivation all had a major influence on the distribution of P which is attributed to differing intensities of pedogenic processes such as weathering and leaching, and their relationship to P transformations in the soil environment.

Introduction

The physical, chemical, and biological processes in soils, which collectively represent the pedogenic processes, interact with the cycles of the major nutrients to influence the amounts and forms found in a given soil. Pedogenic processes have a strong influence on rates of nutrient supply in plant available form and the mechanisms by which they are retained (Anderson 1987). Observed differences in the quantity of soil P have been related to pedogenic processes such as weathering and leaching (Smeck 1973, 1985). Application of a pedogenic index to soils in Western Canada has shown a loss of about 40% of the original total P during pedogenesis in boreal forest soils compared to losses of 23% for less weathered soils developed under grassland (St. Arnaud et al. 1988). The mechanisms involved require further attention, as the nature of the interactions between pedogenic processes and the soil P cycle are less well understood than their overall effect.

The main objective of this study was to better understand P cycling processes in Western Canadian soils. We consider the effect of profile depth, climate, vegetation, and cultivation on the distribution of soil P among different inorganic and organic forms. The patterns observed are equated

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with pedogenic processes as they affect the nature and transformations of P in the soil P cycle. Such transformations play a critical role in governing the bioavailability of P in grassland and forest ecosystems.

Site description

In Saskatchewan, Canada, a narrow environmental gradient of increasing moisture effectiveness from semi-arid grassland in the southwest to sub-humid forest in the northeast has resulted in the formation of soils which vary in profile characteristics and nutrient cycling patterns (Bettany et al. 1973, 1979). Two sites were chosen: one in the Brown soil zone representing a semi-arid grassland, and the other in the Gray soil zone representing a sub-humid boreal forest (Fig. 1). At both sites, the parent material is medium-textured (loam-clay loam), unsorted glacial till. Adjacent north-

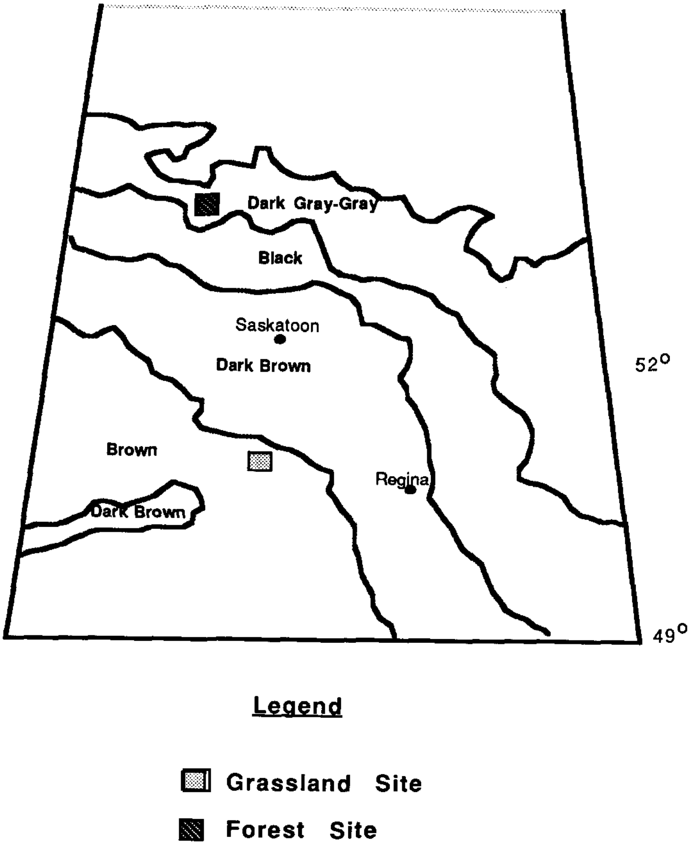

Fig. 1. Soil zones in Saskatchewan and location of study sites.

facing slopes about 100 m long with a gradient of about 8% were selected to permit the comparison of native versus cropping (70 years cereal-fallow) management practices at each site. The native catenas were pristine examples of the natural vegetation in the area prior to settlement, being essentially undisturbed by man. The cultivated sites had received no fertilizer inputs or manuring during the period of cultivation.

Grassland site

Precipitation at the grassland site is about 300–350 mm per year, and evaporative losses are high due to high temperatures and wind speeds. The dominant vegetative species at the upper and mid slope positions of the native grassland catena was blue grama grass (*Bouteloua gracilis*), common to drier parts of the mixed grass prairie. At the lower slope position, the vegetation consisted of hydrophilic forbs and grasses. The soils at the upper and mid slope positions of the grassland catenas were classified as Brown Chernozemic soils (approximate U.S. equivalent: Aridic Haploboroll), and at the lower slope positions, as Humic Luvic Gleysols (approximate U.S. equivalent: Argiaquoll). The lower slope of the grassland site is a depressional area, submerged with water about 5 out of 10 years depending on the amount of snowfall. Water from runoff accumulates in the depression in spring and drains downward through the soil profile during summer and fall. Thus, the lower slope Gleysols are highly leached and show signs of prolonged anaerobic or reducing conditions by the presence of gleying or mottles. The Gleysol on the lower slope of the cultivated catena is usually planted to cereal crops when dry in the spring (about 5 out of every 10 years).

A hydraulic coring device was used for sampling the Chernozemic soils by genetic horizon at the upper and mid slope positions. Five soil cores were randomly sampled within a 5 m radius at each slope position in both the native and cultivated soils. Cores were later bulked by genetic horizon for analyses. The Gleysol at the lower slope position was too wet to allow sampling using the coring device, so the soil was sampled from a pit.

Forest site

At the boreal forest site, precipitation ranges from 400–450 mm per year, and its effectiveness in soil development is much greater than at the grassland site due to lower temperatures and wind speeds. Aspen (*Populus tremuloides*) is the canopy vegetation, green alder (*Alnus crispa*) the upper storey, and the middle and lower stories comprise various grasses and

Table 1. Horizon depth, particle size distribution, and pH of the soils.

Soil	Slope position	Genetic horizon	Depth cm	sand	silt %	clay	pH
Native grassland catena							
Brown Chernozem	Upper	Ah	0–15	31.5	37.7	30.8	6.9
		Bmk	15–30	35.6	34.6	29.8	8.1
		Cca	30–45	32.8	39.2	28.1	8.5
		Ck	45–70	33.5	40.9	25.6	8.7
		Cksa	70–90	32.3	42.0	25.8	8.5
	Mid	Ah	0–14	25.2	36.4	38.4	6.5
		Bm	14–25	25.7	32.6	41.7	7.6
		Bmk	25–40	14.3	37.1	48.6	8.1
		Cca	40–70	12.1	38.1	49.8	8.5
		Cksa	70–90	32.2	40.6	27.2	8.6
Gleysol	Lower	L-H	0–5	–	–	–	5.5
		Ahe	5–15	20.5	43.2	36.4	5.4
		Aheg	15–27	23.0	40.9	36.1	5.9
		Btg	27–70	22.4	39.3	38.2	6.8
Cultivated grassland catena							
Brown Chernozem	Upper	Ap	0–15	45.9	31.6	22.6	7.8
		Bm	15–27	51.4	27.4	21.2	7.8
		Ck	27–50	55.2	25.9	18.9	8.4
	Mid	Ap	0–15	44.2	33.9	21.9	7.4
		Bm	15–39	36.4	39.9	23.6	6.9
		Ck	39–50	32.0	40.5	27.6	8.4
		Cksa	50–70	35.8	34.8	29.4	8.6
Gleysol	Lower	Ap	0–15	33.7	35.7	30.6	5.8
		Aheg	15–40	17.1	48.1	34.7	5.8
		Btg	40–70	13.2	43.5	43.3	5.6
Native aspen forest catena							
Gray Luvisol	Upper	L-H	0–5	–	–	–	5.8
		Ae	5–17	56.5	36.2	7.3	4.9
		Bt	17–68	44.4	24.4	31.2	4.5
		Ck	68–95	46.0	26.6	27.4	7.9
	Mid	L-H	0–5	–	–	–	5.8
		Ae	5–13	26.1	63.3	10.6	4.9
		Bt	13–90	20.4	48.5	31.1	4.7
		Ck	90–105	44.8	27.4	27.7	7.9
	Lower	L-H	0–7	–	–	–	6.0
		Ae	7–21	24.9	65.5	9.6	5.0
		Bt	21–70	43.7	23.3	33.0	5.6
		Cca	70–90	54.4	24.4	21.1	8.1

Table 1. Continued

Soil	Slope position	Genetic horizon	Depth cm	sand	silt %	clay	pH
			Cultivated aspen forest catena				
Gray Luvisol	Upper	Ap	0–7	49.0	29.0	21.9	6.3
		Bt	7–48	42.2	24.5	33.3	6.2
		Ck	48–70	44.5	27.1	28.4	8.0
	Mid	Ap	0–16	37.5	48.0	14.5	5.8
		Bt	16–65	41.3	26.6	32.1	5.5
		Ck	65–95	46.2	27.9	25.9	7.8
	Lower	Ap	0–17	38.8	48.2	13.0	5.7
		Bt	17–80	40.3	24.0	35.7	6.1
		Ck	80–104	43.2	27.9	28.8	7.8

legumes. Soils were sampled by genetic horizon from soil pits at the upper, mid and lower slope positions of the native aspen forest and cultivated catenas. The soils at all three slope positions were classified as Orthic Gray Luvisols (approximate U.S. equivalent: Typic Cryoboralf).

Methods

Sample processing

The soil samples grouped by site, genetic horizon, and slope position, were air-dried and ground to pass a 2 mm sieve. These samples were used in the measurement of particle size distribution and pH (Table 1). Subsamples ground to pass a 0.15 mm sieve were used in the sequential P extraction described in the following section.

Sequential P extraction

A sequential extraction procedure developed by Hedley et al. (1982) to fractionate P into various labile and stable inorganic (P_i) and organic (P_o) forms was employed in this study (Fig. 2).

Inorganic P which is directly exchangeable with solution P and thus of high biological availability is first extracted with anion exchange resin (Amer et al. 1955; Bowman et al. 1978). The residue of the resin extraction is then extracted with $NaHCO_3$, which removes labile P_o and P_i held adsorbed to soil colloids (Bowman & Cole 1978a). The $NaHCO_3$ extract is followed by a NaOH extract to remove more resistant P_o associated with humic compounds and P_i held more strongly by chemisorption to Fe and Al components of soil surfaces (McLaughlin et al. 1977; Bowman & Cole 1978b).

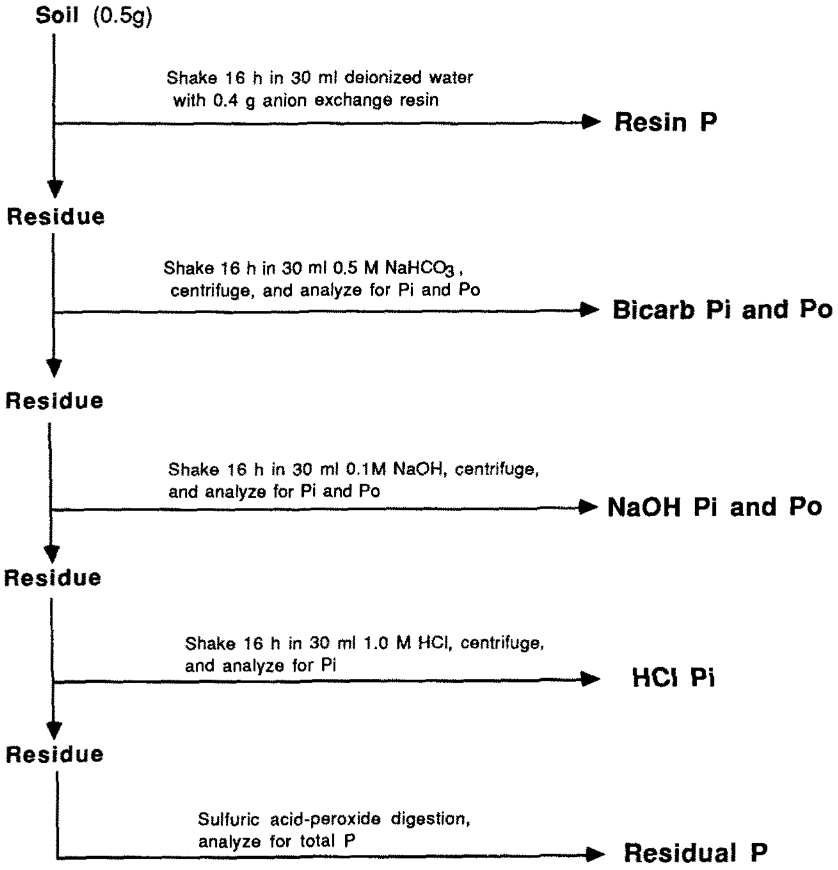

Fig. 2. Flow chart of P sequential extraction procedure.

The residue of the NaOH extract is then extracted with HCl to remove the more stable P minerals of very low solubility such as apatite (Williams et al. 1971). The residue of this extract, believed to be composed of highly resistant P_o and P_i of very low bioavailability, was digested in a sulfuric acid-peroxide digest (10 hrs, 360 °C). Total P in the $NaHCO_3$ and NaOH extracts was also determined by digestion. Orthophosphate ions were measured by the acid molybdate blue color development described by Murphy & Riley (1962). Concentrations of inorganic P in the extracts were subtracted from total P to derive values for organic P.

The above analyses were performed in triplicate (coefficient of variation of less than 5%), and the means reported. An estimate of erosion in the grassland and forest catenas was obtained using the ^{137}Cs assay technique of deJong et al. (1982).

Results and discussion

Effect of profile depth, climate, and vegetation

The proportion of soil P held in labile forms (resin P_i; bicarb P_i, P_o) decreased from surface to subsurface horizons in all profiles (Table 2). This trend can be explained by greater weathering of primary mineral P (apatite) in surface horizons since phosphate derived from weathering of primary minerals enters the solution P_i pool where it may precipitate to form secondary P minerals of high solubility (labile P_i) or be assimilated and converted to organic (biomass) P by plants and microorganisms (Smeck 1985). A portion of the organic P formed is readily hydrolyzed to inorganic form or re-assimilated by other microorganisms (labile P_o) (Chauhan et al. 1981). Cycling of P through the biomass via immobilization-mineralization reactions maximizes the occurrence of inorganic P in labile secondary forms (Walker & Syers 1976). It is likely that this process would be most effective in the surface horizons where plant roots are concentrated and biological activity is highest.

Labile inorganic and organic P forms (resin P_i, bicarb P_i and P_o) made up only a small proportion of the total quantity of P present (Table 2); no single fraction comprised more than 10% of the total P in the mineral horizons. This is consistent with work by Tiessen et al. (1983) in which only 5% of the total P in a grassland soil appeared in labile inorganic fractions (resin, bicarb). The proportion of total P in the most labile inorganic P fractions (resin P_i and bicarb P_i) was highest ($> 20\%$) in the L-H horizons of the Luvisol. Large concentrations of P in the resin extract of the L-H horizon can be attributed to lack of fixation of inorganic P as Fe, Al, and Ca phosphates in these organic horizons. Since the majority of the aspen roots are located directly beneath the litter layer in the Ae horizon, much of the P assimilated by these plants may be derived from phosphate that is mineralized in the L-H horizons and leached into the Ae horizon. The Gleysol L-H and A horizons also contained a high proportion of P in labile inorganic and organic forms which may be attributed to the large quantity of organic P in these soils, replenishing the labile inorganic P pools through mineralization and the labile organic P pools through mobilization of low molecular weight material.

HCl-extractable P represents the fraction of soil P in the form of stable primary minerals, mainly apatite; a calcium phosphate that contains various amounts of carbonate, fluoride, and other anions and cations. In all soil profiles, the proportion of soil P contained in the HCl extract increased from A to C horizons (Table 2). This trend was most pronounced in the Luvisolic

Table 2. Proportion of total P contained in sequentially extractable fractions.

Slope position	Genetic horizon	Resin	Bicarb		NaOH		HCl	Residual	Sum^a (Total)
		Pi	Pi	Po	Pi	Po	Pi	P	P
					% of Total P				mg/kg
Native Brown Chernozem (Aridic Haploboroll)									
Upper	Ah	3.2	1.2	1.7	3.9	7.9	41.7	40.2	666
	Bmk	0.8	0.7	0.8	0.9	2.8	63.2	30.8	729
	Cca	0.4	0.5	0.4	0.7	0.7	78.8	18.6	672
	Ck	0.3	0.3	0.1	0.6	0.3	80.0	18.4	649
	Cksa	0.3	0.7	0.2	0.9	0.9	81.3	15.7	648
Mid	Ah	2.7	1.3	2.1	3.8	7.9	35.0	47.3	721
	Bm	1.1	0.4	1.2	1.7	6.5	50.6	38.6	690
	Bmk	0.9	0.5	0.6	0.9	2.0	68.3	26.9	847
	Cca	0.4	0.3	0.2	0.6	0.9	77.9	19.7	883
	Cksa	0.2	0.6	0.1	1.0	1.0	80.3	16.9	605
Cultivated Brown Chernozem									
Upper	Ap	2.7	1.2	1.1	2.5	7.5	45.1	39.8	541
	Bm	1.2	0.4	1.1	1.5	7.9	48.5	39.5	491
	Ck	1.0	1.1	0.5	0.8	1.9	68.2	26.6	578
Mid	Ap	4.3	1.7	1.2	3.6	8.2	40.0	41.0	540
	Bm	1.5	0.9	1.9	2.3	9.7	37.8	46.0	467
	Ck	0.2	0.3	0.3	0.5	1.0	72.7	25.1	596
	Cksa	0.2	0.7	0.1	0.6	0.4	75.8	22.3	567
Native Gleysol (Argiaquoll)									
Lower	L-H	7.8	5.5	8.2	6.4	29.4	17.4	25.4	993
	Ahe	5.4	4.7	5.3	10.4	14.5	20.9	39.0	830
	Aheg	2.9	2.6	2.9	4.9	7.7	38.9	40.1	498
	Btg	1.4	1.3	1.1	4.6	4.2	38.0	49.4	413
Cultivated Gleysol									
Lower	Ap	8.9	10.4	2.7	10.0	11.2	29.2	27.6	769
	Aheg	9.2	10.1	6.5	19.4	18.9	18.8	17.0	995
	Btg	7.9	9.5	6.0	18.6	11.7	26.6	19.8	822
Native Gray Luvisol (Typic Cryoboralf)									
Upper	L-H	17.3	7.1	9.8	4.0	31.0	6.1	24.7	1061
	Ae	2.7	2.9	8.6	10.0	18.2	25.6	32.2	204
	Bt	1.2	0.7	3.6	4.9	6.9	28.4	54.3	258
	Ck	0.3	0.4	0.3	0.7	1.1	78.5	18.8	595
Mid	L-H	16.8	6.6	9.4	4.4	30.7	6.8	25.3	1146
	Ae	2.1	2.2	6.5	8.8	15.2	16.1	49.2	218
	Bt	0.8	0.6	4.1	4.5	7.9	19.5	62.5	288
	Ck	0.3	0.2	0.5	0.7	0.7	78.3	19.4	567
Lower	L-H	16.7	5.8	6.5	4.4	30.9	6.2	29.6	1175
	Ae	3.0	4.1	5.0	18.9	8.6	28.8	31.5	298
	Bt	0.8	0.7	2.2	4.1	5.2	40.3	46.8	339

Table 2. Continued

Slope position	Genetic horizon	Resin	Bicarb		NaOH		HCl	Residual	Sum[a] (Total)
		Pi	Pi	Po	Pi	Po	Pi	P	P
					% of Total P				mg/kg
	Cca	0.3	0.4	0.7	0.4	1.6	72.8	23.9	485
				Cultivated Gray Luvisol					
Upper	Ap	11.4	5.5	2.7	8.4	9.6	19.6	42.8	427
	Bt	1.0	0.7	1.6	3.0	4.4	47.7	41.5	353
	Ck	0.7	0.1	0.3	0.5	0.7	78.8	18.9	551
Mid	Ap	3.2	2.6	3.3	6.9	10.3	26.3	47.4	304
	Bt	1.3	1.2	1.1	5.5	2.4	47.2	41.4	388
	Ck	0.3	0.1	0.2	0.7	0.8	78.0	19.8	569
Lower	Ap	4.7	3.4	4.0	9.6	9.5	29.9	39.0	340
	Bt	2.6	1.3	1.2	3.3	3.1	54.2	34.4	415
	Ck	0.7	0.6	0.5	1.3	1.5	75.2	20.3	619

[a] Total P is closely approximated by the sum of the individual fractions (Tiessen et al. 1983).

profiles; with 20 to 30% HCl-extractable P in the A horizons and 75 to 80% of the P in this form in the Ck horizons. A similar increase in the acid-extractable P fraction with increasing depth was found in five cultivated Saskatchewan soil profiles (Roberts et al. 1985). The lower percentage of P in stable primary forms in the surface horizons is explained by greater release of P from apatite due to more intense weathering at the surface. This P is subsequently converted to secondary P_i forms or immobilized by plants and microorganisms to appear as organic P (Tiessen & Stewart 1985).

Consistent with the greater weathering intensity in the Luvisol and Gleysol, lower proportions of HCl-extractable P were found in the A and B horizons of these profiles ($< 40\%$) than in the Chernozem ($> 40\%$). In the L-H horizons of the Luvisol, HCl-extractable P made up about 6% of the total P. Since these horizons are organic, the inorganic P in the HCl extract was likely derived from organic phosphate groups by hydrolysis.

The NaOH extract removes secondary Fe and Al associated phosphates (Hedley & Stewart 1982). The high proportion of total P found in the NaOH P_i fraction of the Gleysol and Luvisol A and B horizons (5–19%) compared to the Chernozem solum (2–4%) (Table 2) is in agreement with the tendency towards greater amounts of secondary Fe and Al – P forms in more highly weathered soils (Sadler & Stewart 1975; Arshad & St. Arnaud 1980).

NaOH P_o represents the organic P held in more resistant or humified forms such as humic acids (Bowman & Cole 1978b). The quantity of NaOH P_o was about four times the amount held as bicarb P_o in the genetic horizons of the soil profiles. Other work has shown NaOH P_o to be the largest single fraction of organic P in the soil (Roberts et al. 1985). The proportion of NaOH P_o was highest in the surface horizons and decreased with increasing profile depth (Table 2), similar to the bicarb P_o fraction. This can be attributed to greater weathering and conversion of released P to organic forms in biologically active surface horizons.

Organic P extractable by $NaHCO_3$ (bicarb P_o) has been shown to be highly labile, consisting of loosely held, low molecular weight organics such as RNA, nucleotides, and glycerophosphates (Bowman & Cole 1978a). A greater proportion of the organic P was present in the bicarbonate fraction as depth in the profiles increased (Table 3), consistent with the narrower C:P ratios and increased proportion of fulvic acid P observed at depth in these profiles in an earlier study (Schoenau & Bettany 1987). This trend is attributed to leaching of low molecular weight, labile, P-rich organics from zones of production in surface horizons to zones of accumulation in B and C horizons. Such a process could over 10000 years of soil development constitute a significant export of P from the solum and may explain the losses of P over pedogenesis observed by St. Arnaud et al. (1988) in similar soils.

Up to 60% of the total P is present in the residual fraction (Table 2). A considerable portion of the residual P is likely resistant organic P that is strongly associated with the mineral fraction, since the $NaHCO_3$ and NaOH extracts do not remove all the organic matter associated with inorganic colloids (Hedley et al. 1982). In support of this, Tiessen et al. (1983) found that about 70% of the P in the residual fraction of the surface horizon of a grassland soil was in organic form. The residual fraction probably does not make a large direct contribution to solution P but may be important over the long term by replenishing the supply of labile organic P in the bicarb and resin fractions via oxidation and breakdown reactions.

In the native and cultivated Chernozem profiles, the residual fraction was largest in the surface horizons and decreased with depth to the C horizons (Table 2). The decrease in the proportion of total P in the residual fraction parallels the decrease in the percentage of P in the NaOH P_o and $NaHCO_3$ P_o fractions, which would be expected if the residual fraction were composed mainly of organic P. The proportion of residual P did not decrease consistently with depth in the Gleysol and Luvisol profiles, but peaked in the Bt horizons. A significant proportion of the residual P in the highly weathered Ae and Bt horizons could be comprised of resistant inorganic P bonded to amorphous Al and Fe sesquioxides as well as resistent clay and sesquioxide-associated organic P. Increased conversion of labile secondary P forms

Table 3. Bicarb P_o as a percentage of organic P (bicarb P_o + NaOH P_o) in genetic horizons.

Slope	Horizon	Bicarb P_o %	Slope	Horizon	Bicarb P_o %
	Native Chernozem			Cultivated Chernozem	
Upper	Ah	18	Upper	Ap	13
	Bmk	22		Bm	12
	Cca	38		Ck	19
	Ck	24			
	Cksa	20			
Mid	Ah	21	Mid	Ap	13
	Bm	15		Bm	16
	Bmk	23		Ck	22
	Cca	19		Cksa	19
	Cksa	–			
	Native Gleysol			Cultivated Gleysol	
	L-H	22		Ap	20
	Ahe	27		Aheg	26
	Aheg	27		Btg	34
	Btg	21			
	Native Gray Luvisol			Cultivated Gray Luvisol	
Upper	L-H	24	Upper	Ap	22
	Ae	32		Bt	27
	Bt	35		Ck	32
	Ck	18			
Mid	L-H	23	Mid	Ap	24
	Ae	30		Bt	31
	Bt	34		Ck	17
	Ck	43			
Lower	L-H	17	Lower	Ap	29
	Ae	37		Bt	27
	Bt	29		Ck	25
	Cca	32			

(resin P_i, bicarb P_i, and NaOH P_i) to highly occluded P minerals would explain the decrease in labile P forms and the increase in residual P from Ae to Bt horizons (Table 2).

Effect of cultivation

Seventy years of cereal-fallow cultivation reduced the concentrations of total P in the A horizons of the upper and mid slope Chernozem by 125 $mg \cdot kg^{-1}$ (19%) and 181 $mg \cdot kg^{-1}$ (25%) (Table 4). Hedley et al. (1982)

Table 4. Changes in P concentration in the sequentially extracted P fractions of the Chernozem A horizons as a result of 70 years wheat-fallow cultivation.

Resin	Bicarb		NaOH		HCl	Residual	Sum P
Pi	Pi	Po	Pi	Po	Pi	P	
Change as a percent of native P fraction							
Upper slope							
−33	−20	−47	−48	−23	−12	−20	−19
Mid slope							
+19	−3	−56	−29	−22	−14	−35	−25

observed a similar reduction (29%) in total P concentration in the surface horizon of a Black Chernozem following 65 years of cropping in a wheat-wheat-fallow rotation. In their study, export of P in grain and straw accounted for most (> 75%) of the loss, and the remainder was attributed to erosion. In this catena, ^{137}Cs measurements indicated that loss of soil by wind or water erosion was negligible since 1960. Thus, the reduced concentration of total P can be ascribed to the export of P in grain.

Most (65–75%) of the P loss occurred from the organic P fraction. Other workers (Hedley et al. 1982; Tiessen et al. 1982, 1983) have also observed that most of the difference in total P between paired native and cultivated grassland soils was accounted for by the organic P fraction. The reduction in organic P in cultivated grassland soils may be explained by accelerated rates of organic P decomposition and reduced residue inputs in the crop-fallow system. The lower C input in the cultivated soil has the effect of reducing the amount of inorganic P incorporated back into the organic form.

The cultivated Chernozem upper slope A horizon contained considerably less P in the labile P_i fractions (resin, bicarb) than its native counterpart (Table 4). This is consistent with other work which has shown large reductions in the quantity of P held in labile P_i fractions following prolonged cultivation (Hedley et al. 1982; Tiessen et al. 1983). At the mid slope position located a few meters away, the resin P_i fraction in the cultivated soil contained 19% more P than its native equivalent and the bicarb P_i was only 3% lower.

The largest reduction (47–56%) in an individual P fraction occurred in the bicarb P_o fraction (Table 4). The NaOH P_o fractions in the cultivated soils were about 23% lower than in the native soils. Tiessen et al. (1983) have also found proportionately greater losses of organic P from the bicarbonate fraction than the more stable NaOH fraction during cultivation. This trend is consistent with higher rates of organic matter decomposition and loss of easily mineralized constituents in cultivated soils (Dormaar 1979; Campbell & Souster 1982).

The amounts of P in the residual fractions of the upper and mid slope A horizons decreased by 20 and 35 percent as a result of cultivation (Table 4). The contribution of the residual P loss to the total P reduction was larger than from any other fraction (42 and 66%, upper and mid slopes), attesting to the importance of this fraction in replenishing plant available P, either directly or indirectly, throughout the cultivation period.

The largest single inorganic P fraction, HCl P_i, was 12 to 14% lower in the cultivated soil. Hedley et al. (1982) noted a similar decrease in HCl P_i in soils cultivated for an equivalent period of time. This suggests that mineral weathering is enhanced as a result of cultivation. The release of H^+ ions by plant roots and the subsequent solubilization of apatite P may accelerate the release of P from the HCl fraction.

Conclusions

The distribution of soil P among various inorganic and organic forms is markedly affected by profile depth, climate, vegetation, and cultivation. The observed differences in the distribution and amounts of P reflect differing intensities of pedogenic processes such as weathering, leaching, and organic matter decomposition. These pedogenic processes interact with the soil P cycle to influence the nature of P in the soil-plant systems. Through examination of these interactions in Western Canadian soils, a better understanding of P cycling processes has been achieved.

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References

Amer F, Bouldin DR, Black CA & Duke FR (1955) Characterization of soil phosphorus by anion exchange resin adsorption and ^{32}P equilibrium. Plant and Soil 6: 291–408

Anderson DW (1987) Pedogenesis in the grassland and adjacent forests of the Great Plains. Advances in Soil Science 7: 53–93

Arshad MA & St. Arnaud RJ (1980) Occurrence and characteristics of ferromanganiferous concretions in some Saskatchewan soils. Can. J. Soil Sci. 60: 685–695

Bettany JR, Stewart JWB & Halstead EH (1973) Sulfur fractions and carbon, nitrogen, and sulfur relationships in grassland, forest, and associated transitional soils. Soil Sci. Soc. Am. Proc. 37: 915–918

Bettany JR, Stewart JWB & Saggar S (1979) The nature and forms of sulfur in organic matter fractions of soils selected along an environmental gradient. Soil Sci. Soc. Am. J. 43: 481–485

Bowman RA & Cole CV (1978a) Transformations of organic phosphorus substances in soil as evaluated by sodium-bicarbonate extraction. Soil Sci. 125: 49–54

Bowman RA & Cole CV (1978b) An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Sci. 125: 95–101

Bowman RA, Olsen SR & Watanabe FS (1978) Greenhouse evaluation of residual phosphate by four phosphorus methods in neutral and calcareous soils. Soil Sci. Soc. Am. J. 42: 451–454

Campbell CA & Souster W (1982) Loss of organic matter and potentially mineralization nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. 62: 651–656

Chauhan BS, Stewart JWB & Paul EA (1981) Effect of labile inorganic phosphate status and organic carbon additions on the microbial uptake of phosphorus in soils. Can. J. Soil Sci. 61: 373–385

DeJong E, Villar H & Bettany JR (1982) Preliminary investigations on the use of ^{137}Cs to estimate erosion in Saskatchewan. Can. J. Soil Sci. 62: 673–683

Dormaar JF (1979) Organic matter characteristics of undisturbed and cultivated Chernozemic and Solonetzic A horizons. Can. J. Soil Sci. 59: 349–356

Hedley MJ & Stewart JWB (1982) A method to measure microbial phosphorus in soils. Soil Biol. Biochem. 14: 377–385

Hedley MJ, Stewart JWB & Chauhan BS (1982) Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46: 970–976

McLaughlin JR, Reyden JC & Syers GK (1977) Development and evaluation of a kinetic model to describe phosphate sorption by hydrous ferric oxide gels. Geoderma 18: 295–307

Murphy J & Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27: 31–36

Roberts TL, Stewart JWB & Bettany JR (1985) The influence of topography on the distribution of organic and inorganic soil phosphorus across a narrow environmental gradient. Can. J. Soil Sci. 65: 651–665

Sadler JM & Stewart JWB (1975) Changes with time in form and availability of residual fertilizer phosphorus in a catenary sequence of Chernozemic soils. Can. J. Soil Sci. 55: 149–159

Schoenau JJ & Bettany JR (1987) Organic matter leaching as a component of carbon, nitrogen, phosphorus, and sulfur cycles in a forest, grassland, and gleyed soil. Soil Sci. Soc. Am. J. 51: 646–651

Smeck NE (1973) Phosphorus: an indication of pedogenetic weathering processes. Soil Sci. 115: 199–206

Smeck NE (1985) Phosphorus dynamics in soils and landscapes. Geoderma 36: 185–199

St. Arnaud RJ, Stewart JWB & Frossard E (1988) Application of the pedogenic index to soil fertility studies. Geoderma 43: 21–32

Tiessen H & Stewart JWB (1985) The biogeochemistry of soil phosphorus. In: DE Caldwell et al (Eds) Planetary Ecology (pp 463–472) Van Nostrand and Reinhold, New York

Tiessen H, Stewart JWB & Cole CV (1984a) Pathways of P transformations in soils of differing pedogenesis. Soil Sci. Soc. Am. J. 48: 853–858

Tiessen H, Stewart JWB & Moir JO (1983) Changes in organic and inorganic phosphorus composition of two grassland soils and their particle size fractions during 60–90 years of cultivation. J. Soil Sci. 34: 815–823

Tiessen H, Stewart JWB & Bettany JR (1982) Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorus in grassland soils. Agron. J. 74: 831–835

Walker TW & Syers JK (1976) The fate of phosphorus during pedogenesis. Geoderma 15: 1–19

Williams JDH, Syers JK, Harris RF & Armstrong DE (1971) Fractionation of inorganic phosphate in calcareous lake sediments. Soil Sci. Soc. Am. J. 35: 250–255