



'ACCUMULATION OF PLANT NUTRIENTS IN SANDY SOILS'

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SUMMARY

This thesis deals with the accumulation of plant nutrients and changes in some soil properties as affected by pasture development and superphosphate application. The investigation was carried out on the siliceous sandy soils of the South East of South Australia.

The techniques and methods used in selecting paddocks that had been developed for different lengths of time are described.

Measurements of total phosphorus accumulation in the various soil layers, illustrated the importance of leaching in these sandy soils. In fact, for every 9 kg ha^{-1} phosphorus applied only 3.4, 3.2 and 2.0 kg ha^{-1} accumulated in the 0-10 cm soil layer for the Hundreds of Senior, Willalooka and Coles respectively. The reasons for these high leaching losses and differences between areas is discussed.

Similarly, sulphur accumulation in these soils was affected by leaching and recoveries ranged from 42 percent for the Hundred of Coles to 63 percent for the Hundred of Willalooka.

Although no fertilizer nitrogen had been applied to these soils, total nitrogen accumulated at rates of 55, 48 and $37 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for the Coles, Willalooka and Senior Hundreds respectively.

Increases in the accretion of total calcium, organic carbon and available phosphorus occurred with time and superphosphate. Cation exchange capacity increased with time, while the pH levels in the various Hundreds fell.

The C:P, N:P and S:P ratios all declined with years of pasture development, reaching an equilibrium after approximately 10 years. The significance of this finding in relation to measuring when a soil has reached maintenance phase is discussed.

The results derived in the investigation were used to determine maintenance phosphorus requirements using a balance sheet approach. Calculated maintenance superphosphate values for grazed pastures were 125, 70 and $50 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for the Coles, Willalooka and Senior Hundreds respectively.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University, and to the best of the author's knowledge and belief, the thesis contains no material previously published or written by another person, except when due reference is made in the text of the thesis.

Dale C. Lewis

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INTRODUCTION



With large increases in the price of superphosphate in recent years, it is essential to know accurately the minimum rates of superphosphate required to maintain optimum pasture growth and hence animal production. Large areas of south eastern South Australia consist of siliceous sands, and the requirements for superphosphate of these soils are higher than for any other soil type in the area. This is due in part to the large leaching losses of both phosphorus and sulphur as well as losses in fixation and animal removal.

Extensive tracts of this siliceous sand country have been sown to pasture in the last 30 years, and during that time it has been common practice to apply superphosphate at rates up to 200 kg ha⁻¹ annually. This has resulted in a general build up in soil fertility, both organic and inorganic nutrients, to a stage where annual superphosphate dressings can be reduced. The magnitude of these annual 'maintenance' dressings can be determined by measuring the amounts of phosphorus and sulphur depleted from the system (Clarke, 1969). With the average rainfall varying from 400 mm in the Upper South East to 800 mm in the Lower South East, it would be expected that losses would vary in the area, i.e. due to differences in leaching, fixation and animal removal. Hence the 'maintenance' superphosphate rates would also be expected to vary considerably in the area. Pasture species will also have a bearing on the rates and in some cases the frequency of superphosphate application. For example lucerne, due to its deep rooting nature is able to retrieve nutrients leached down the soil profile, that would be otherwise lost to shallow rooting annuals such as subterranean clover. Hence in most cases lucerne will have a reduced requirement for superphosphate in the maintenance phase.

In this thesis the literature review lays the background for understanding the changes that occur in nutrient accumulation with continued applications of superphosphate, the likely fate of applied fertilizer and how this information can be used to maintain the productivity of grazed pastures. The thesis describes the collection of soil samples from three areas in the South East, the analysis of these samples and how the results can be used in preparing a balance sheet, as an aid to assessing maintenance superphosphate requirements for pastures growing on the siliceous sands.

REVIEW OF LITERATURE

I. Agricultural history of the siliceous sands in the south east of South Australia

Development of the siliceous sands for agriculture in the South East was at first disappointing. This was in part due to the very low phosphorus status of these soils, values of 0.003 to 0.005 percent being quite common in the surface 10 cm of sands in the Lower South East (Crocker and Tiver, 1946; Clarke, 1965). Similar values were reported for sands in the Upper South East (Taylor, 1933; Coaldrake, 1951; Clarke, 1966). The use of superphosphate alleviated many of these phosphorus deficiencies (Anderson and Neal-Smith, 1951).

Nitrogen contents were also low in virgin soils and limited the growth of non legumes (Riceman, 1948; Anderson and Neal-Smith, 1951). Therefore it was important that a vigorously growing legume plant was introduced into the pasture. Early attempts were discouraging as the legume component e.g. subterranean clover failed to thrive and commonly died within two years. Lucerne persisted but did not grow vigorously in spite of liberal superphosphate dressings (Riceman, 1948). The discovery of the need for both copper and zinc by legume species paved the way for the establishment of highly productive pastures (Riceman and Anderson, 1943 a; Riceman and Anderson, 1943 b; Riceman, 1948). Benefits were also gained from the use of other trace elements, in particular cobalt and molybdenum (Tiver, 1958). Yield responses to both lime and potassium have also been recorded (Tiver, 1958; Lines and Marrett, 1962).

Continued applications of superphosphate and trace elements to legume based pastures growing on the siliceous sands has resulted in increases in soil fertility (Russell, 1962). The rate of build up and factors affecting this accumulation of nutrients constitute the following sections of the literature review.

II. Phosphorus accumulation

1. Rate of accumulation

When superphosphate is applied to the soil, only a portion of the phosphorus is absorbed by plants. This phosphorus can then be removed from the site in animal or plant products or returned to the soil as organic phosphorus. The residual phosphorus in the soil consists of this organic fraction as well as the inorganic phosphorus supplied as superphosphate but not taken up by the plants. The rate of accumulation of phosphorus therefore depends on the fate of both plant absorbed and inorganic phosphorus.

Soil texture has an important bearing on the accumulation of phosphorus (Jackson, 1966). In soils of coarse texture e.g. the siliceous sands, that fraction not absorbed by plants can be leached rapidly (Hingston, 1959; Russell, 1960 b; Paton and Loneragan, 1960; Ozanne, Kirton and Shaw, 1961). However, in finer textured soils phosphorus is not lost in this way and nearly all of the applied phosphorus can be accounted for in the surface layers (Williams, 1950; Woodroffe and Williams, 1953; Donald and Williams, 1954; Williams and Donald, 1957). The investigation by Donald and Williams (1954) on podzolic soils in the Crockwell district of New South Wales revealed that within experimental error, all of the phosphorus applied over many years could be accounted for within 10 cm of the soil surface. Total phosphorus accumulated at the rate of 7.5 ppm for each 125 kg ha⁻¹ of superphosphate applied. Williams (1950 a) working at the Waite Institute found that nearly all the phosphorus applied to a red-brown earth over many years was retained in the top 15 cm of soil under sown pasture. Therefore, in these soils the rate of build up is dependent on the amount of superphosphate applied.

Hingston (1959) examined the fate of phosphorus applied to sandy soils of the Swan Coastal Plain in Western Australia. For the Coolup sand, which had received 6900 kg ha^{-1} of superphosphate, only thirty percent of the phosphorus could be accounted for in the top 20 cm of soil. He obtained similar results for the Boyanup sandy loam where approximately twenty percent of the phosphorus remained in the surface layer. Cook (1939) and Russell (1960 b) working at Kybybolite in South Australia obtained similar results for a solodized solonetz (Table 1). Both workers sampled the same plots that had been established from 1924-26. The results indicate that the rate of accretion of phosphorus decreased with time. After 14 years of superphosphate application at the rate of 100 kg ha^{-1} the accumulation rate was $4.5 \text{ kg phosphorus ha}^{-1} \text{ yr}^{-1}$ in the top 10 cm of soil (Cook, 1939). Sampling the same plot 20 years later, Russell (1960 b) found that the rate of accumulation was $3.1 \text{ kg phosphorus ha}^{-1} \text{ yr}^{-1}$. Results from the plots receiving 201 kg ha^{-1} superphosphate annually showed similar trends, 9.2 as against $4.6 \text{ kg phosphorus ha}^{-1} \text{ yr}^{-1}$.

2. Form of phosphorus

Phosphorus accumulates in the soil as either inorganic or organic forms. The proportion of any one form is affected by land utilization. Under continuous pasture a large percentage of the phosphorus present is in the organic fraction (Williams, 1950; Jackson, 1966; Williams, 1970). However, in cultivated soils, where there is little chance of organic matter accumulation, the residual phosphorus is primarily in the inorganic fraction (Williams, 1950 a).

(a) Organic phosphorus

The major part of soil phosphorus is often organic (Williams, 1970). However, factors such as pH, vegetation, parent rock, drainage and time will affect the accumulation of organic phosphorus.

Under acid conditions, the build up of organic phosphorus is enhanced (Williams and Steinbergs, 1958; John et al., 1965). This is due to a greater iron and aluminium oxide content. Liming the soil may result in a lowering of the organic phosphorus content (Williams and Steinbergs, 1958; Williams et al., 1960). This was not so in a long term soil fertility trial conducted at Kybybolite (Russell, 1960 b). Results presented in Table 2 suggest that liming had no effect on organic phosphorus accumulation.

Both vegetation and parent rock influences the organic phosphorus content of soils (Nye and Bertheux, 1957; Wells and Saunders, 1960; Barrow, 1961; Ipinmidun, 1973; Fares et al., 1974). Impeded drainage, in general, will lower the build up of organic phosphorus (Williams et al., 1960).

The application of superphosphate greatly enhanced the accumulation of organic phosphorus in two South Australian soils (Table 2). While varying the rate had very little effect on the absolute amount of organic phosphorus present. However, Kohn, et al., (1977) found that organic phosphorus levels were not affected by varying either the superphosphate or stocking rates.

Cultivation has the effect of reducing organic phosphorus accumulation. Williams and Lipsett (1961) collected 55 pairs of soils from currently cropped paddocks and adjacent areas that had never been cultivated. They found that the organic phosphorus values for the cultivated paddocks were 16.8 percent lower than for the uncultivated paddocks, presumably a result of increased mineralization due to cultivation.

The largest build up of organic phosphorus occurred under permanent pasture. Jackman (1955 a & b) has shown that as much as 60 percent of applied phosphorus was immobilized in some New Zealand soils. Average conversions are of the order 20-40 percent in the top 2.5 cm of soil.

TABLE 1.

Accumulation of phosphorus in a solodized solonetz at Kybybolite, in plots that were established from 1924-26.

Depth of sample (cm)	Total phosphorus applied kg ha ⁻¹	Period of superphosphate application (yr.)	Phosphorus present in plots at sampling kg ha ⁻¹	Increase in fertilized plots over nil plots at sampling kg P ha ⁻¹	Rate of increase of fertilized plots over nil plots at sampling kg P ha ⁻¹ yr ⁻¹	Reference
0-10	Nil	0	85	-	-	
10-20			53	-	-	
20-30			53	-	-	
0-10	128	14	148	63	4.5	Cook (1939 a & b)
10-20			47	-6	-0.4	
20-30			69	16	1.1	
0-10	219	12	196	111	9.2	
10-20			64	11	0.9	
20-30			69	16	1.3	
0-10	Nil	0	70	-	-	
10-20			52	-	-	
0-10	290	34	174	104	3.1	Russell (1960 b)
10-20			63	11	0.3	
0-10	484	32	217	147	4.6	
10-20			114	62	1.9	

TABLE 2.

Accumulation of organic phosphorus under pasture as affected by time and superphosphate application in South Australian soils.

Location	History of paddock	Depth (cm)	Organic phosphorus		Reference
			ppm	percent of total phosphorus	
Kybybolite S.A.	No phosphorus for 34 years.	0- 5	13	24	Russell (1960 b)
		5-10	6	16	
	Superphosphate for 32 years (484 kg P ha ⁻¹)	0- 5	55	27	
		5-10	30	23	
	Superphosphate for 34 years (290 kg P ha ⁻¹) + lime.	0- 5	51	26	
		5-10	30	30	
Parndana K.I. S.A.	Superphosphate for 12 years (180 kg P ha ⁻¹)	0-10	-	84	Carter (1958)
Urrbrae S.A.	No superphosphate for 11 years	0-10	115	46	Williams (1950 a)
	Superphosphate for 11 years (124 kg P ha ⁻¹)	0-10	127	41	
	Superphosphate for 11 years (248 kg P ha ⁻¹)	0-10	129	38	
	Superphosphate for 11 years (372 kg P ha ⁻¹)	0-10	129	33	
Urrbrae S.A.	Superphosphate for 38 years (603 kg P ha ⁻¹)	0-10	125	30	Steward & Oades (1972)

* N.B. Value in brackets represents total phosphorus applied.

Similar results have been reported in Australia (Williams, 1950; Donald and Williams, 1954; Williams and Donald, 1957). The accretion of organic phosphorus results from the decay of residual plant material or decomposition of dung. Bromfield (1961) found that sheep eating *Danthonia* pastures voided approximately 225-340 g of phosphorus as organic phosphorus per sheep per year. Further studies by Bromfield and Jones (1970) indicated that mineralization and leaching of organic phosphorus deposited in dung was very slow. Due to the uneven manner in which sheep deposit their dung i.e. "camping" (Hilder, 1964), grazing results in areas of high phosphorus content at the expense of larger areas from which phosphorus is depleted. Therefore organic phosphorus accumulation under permanent pasture is often very uneven.

(b) Inorganic phosphorus

Much of the inorganic phosphorus in the soil exists in combinations with aluminium, iron and calcium. Phosphorus can also be adsorbed by iron and aluminium oxides and clay minerals, especially in acid soils (Jackson, 1966). Calcium is the main binding agent in neutral to alkaline soils (Williams, 1970). Calcium phosphates are of some importance in slightly acid soils (John, 1971).

Accumulation of inorganic phosphorus has been measured by a number of workers in Australia (Table 3), whereas the rate of superphosphate addition had little effect on the accumulation of organic phosphorus (Table 2), the accumulation of inorganic phosphorus was affected by the addition of superphosphate (Simpson et al., 1974 and Kohn et al., 1977). Kohn, et al., (1977) showed that the level of aluminium bound phosphate increased at a faster rate than either the iron or calcium phosphates. Other less soluble phosphatic fertilizers have been shown to increase the inorganic phosphorus content at a greater rate than superphosphate (Russell, 1960 b). He found that soil treated with calcium rock phosphate

contained the most acetic acid-extractable-phosphorus, while soil treated with aluminium rock phosphate contained the highest alkali-soluble-inorganic phosphorus.

The accumulation of inorganic phosphorus results primarily from the reversion of applied phosphate fertilizer. However, large amounts are returned to the soil in faeces. Bromfield (1961) found that 1.1 - 1.4 kg of inorganic phosphorus per sheep was returned to the soil annually. Although not soluble in water, this fraction was readily soluble in acid, and Bromfield (1961) found that wheat plants grown in pot culture were able to utilize the phosphorus. The return of inorganic phosphorus to the soil varies with season. In spring the grazing animal recycles most of the ingested inorganic and organic phosphorus as inorganic phosphorus. However, in summer this is not so and sheep do not cause a net mineralization of ingested organic phosphorus (Bromfield and Jones, 1970).

3. Factors affecting rate of accumulation of phosphorus

(a) Leaching

Australian soils in their native state are extremely low in phosphorus, ranging from 0.0001 percent to isolated cases of 0.5 percent, with a great preponderance of values below 0.03 percent (Stephens and Donald, 1958). Wild (1958, 1961) suggested that in many cases these low values are due to the leaching of phosphorus from soils during wetter periods of the past. Large areas of southern Australia consist of siliceous sands and it is in these soils where much of the applied phosphorus fertilizer is leached through the profile by rainfall (Lewis et al., 1974). Paton and Loneragan (1960) using ³²P demonstrated that substantial amounts of phosphorus applied to pots leached down an acid organic sand. Penetration was reduced by applying lime at a rate of 7.5 t ha⁻¹. A number of workers have since measured leaching losses of phosphorus applied in the field. The magnitude of these losses is shown in Table 4.

TABLE 3

Accumulation of inorganic phosphorus under pasture in Australian soils as affected by time and superphosphate application.

Location & reference	History of paddock	Depth (cm)	Inorganic phosphorus (ppm)		
			CH ₃ COOH extn.	NaOH extn.	Steward & Oades extn. (1972)
Kybybolite S.A. (Russell, 1960 b)	No phosphorus for 34 years	0- 5	6	21	-
		5-10	4	10	-
	Superphosphate for 32 years (484 kg P ha ⁻¹)	0- 5	57	69	-
		5-10	32	52	-
Urrbrae, S.A. (Williams, 1950 a)	Superphosphate for 34 years (290 kg P ha ⁻¹) + Lime	0- 5	47	67	-
		5-10	16	34	-
	No superphosphate for 11 years	0-10	18	25	-
	Superphosphate for 11 years (124 kg P ha ⁻¹)	0-10	33	50	-
Ginninderra, A.C.T. Simpson et al., (1974)	Superphosphate for 11 years (248 kg P ha ⁻¹)	0-10	42	60	-
	Superphosphate for 11 years (372 kg P ha ⁻¹)	0-10	73	80	-
	Superphosphate for 7 years (27 kg P ha ⁻¹)	0-7.5	-	-	81
Simpson et al., (1974)	Superphosphate for 7 years (81 kg P ha ⁻¹)	0-7.5	-	-	98
	Superphosphate for 7 years (244 kg P ha ⁻¹)	0-7.5	-	-	198

* N.B. Values in brackets represent total phosphorus applied.

TABLE 4

Leaching losses of applied phosphorus from some Australian soils.

Location and soil type	Duration of trial (yr)	Depth (cm)	Phosphorus applied kg ha ⁻¹	Phosphorus leached (percent of that added)	Reference
Boscable gravel (W.A.)	4	0-10	105	17	
Kojonup gravelly sand (W.A.)	7	0-10	105	22	
Balgarup sand (W.A.)	7	0-10	277	34	Ozanne et al.,
Kojonup sand A (W.A.)	4	0-10	105	43	(1961)
Kojonup sand B (W.A.)	1	0-10	47	67	
Crawley sand (W.A.)	18	0-10	436	76	
Carrolup sand (W.A.)	3	0-10	68	81	
Coolup sand (W.A.)	27	0-15	694	71	
Bojanup sandy loam (W.A.)	20	0-15	242	74	Hingston (1959)
Blythewood sand (W.A.)	3	0-15	81	2	
Solodized solonetz (S.A.)	34	0-20	290	59	
Solodized solonetz (S.A.)	32	0-20	484	55	Russell (1960 b)

Even larger losses than those shown in Table 4 have been reported by Alston and Chin (1974). Losses of superphosphate from the top 10 cm of acid sandy soil at Mt. Compass in South Australia were 100 percent and 80 percent of that applied in superphosphate at rates of 22 and 66 kg P ha⁻¹ respectively. Most of this phosphorus was lost within two months of application.

Leaching losses of phosphorus have been recorded in other countries (Neller, 1946; Neller et al., 1951; Fox and Kamprath, 1971; Logan and McLean, 1973).

(b) Fixation

If phosphorus is to accumulate in sandy soils, it has to be "fixed" in some form that will withstand leaching. In acid soils both aluminium and iron combine with the applied phosphorus. Ballard and Fiskell (1974 a) measured a number of soil properties and found that extractable aluminium and iron provided the best indices of phosphorus retention. On measuring the different forms of both iron and aluminium and relating these to phosphorus retention, they found the order of activity of phosphorus fixation was exchangeable > amorphous > crystalline. Oxalate extractable aluminium was found to account for 81 percent of the variation in phosphorus retention (Ballard and Pritchett, 1974).

Ozanne et al., (1961) also were able to show that retention of phosphorus was related to extractable aluminium, suggesting that the aluminium fraction is important in fixing phosphorus in the acid sandy soils. Both iron and aluminium oxides were found to be important in sorbing phosphate in 26 soils from Kenya (Hinga, 1973) whereas, Sree Ramulu et al., (1967) showed that phosphorus fixation was highly correlated with dithionite extractable iron ($r = 0.77$) and oxalate extractable iron ($r = 0.95$). They concluded that sodium hydroxide extracted aluminium was not related to phosphorus fixation. Since both iron and aluminium oxides exist as a

mixture of both crystalline and amorphous, then correlations for one or the other may not be that useful (Oades, pers. comm.).

Clay minerals are also involved in the fixation of phosphorus (Sree Ramulu et al., 1967). Soils which contained kaolinite as the only clay mineral fixed more phosphorus than soils that contained both vermiculite and kaolinite.

The application of lime to the acid sandy soils markedly reduces the losses of applied phosphorus (Neller, 1946; Neller et al., 1951; Paton and Loneragan, 1960; Clarke, 1974). This is due to a direct increase in soil retention and indirectly, by increasing plant uptake of phosphorus (Ozanne et al., 1961).

(c) Removal in plants and animals

Under a system of grazing, removal of phosphorus will be much lower than a cropping or hay cutting programme (Clarke, 1969). Losses from a grazing system will be either in wool or meat. Russell (1960 b) estimated the removal of phosphorus in animal products from the long term fertility plots at Kybybolite were from 0.17 to 0.58 kg ha⁻¹yr⁻¹. The differences due to fertilizer rate (Table 5). Williams (1962) gave the following figures as approximate phosphorus contents; fleece of wool - negligible; fat lamb - 0.2 kg; 1 tonne clover hay - 2.3 kg and 1000 kg wheat - 2.5 kg. Similar figures have been presented by French et al., (1975).

TABLE 5

Removal of phosphorus in sheep from the long term soil fertility plots at Kybybolite (Russell, 1960 b)

Phosphorus applied (kg ha ⁻¹)	Total liveweight of sheep on plots from 1919 to 1957-58 (kg ha ⁻¹)	Phosphorus removed	
		kg ha ⁻¹	kg ha ⁻¹ yr ⁻¹
Nil	1176	5.8	0.17
290	3517	16.8	0.49
484	3707	18.6	0.58

(d) Form of fertilizer applied

Superphosphate has been the main phosphorus fertilizer in Australia, accounting for 99 percent of all phosphorus fertilizers used (Alston and Chin, 1974). In most situations it is by far the most suitable form in which to apply phosphorus to the soil, as shown in previous sections. Build up of soil phosphorus as a result of applying superphosphate has in most situations been satisfactory. However, on coarse textured soils the accumulation of applied phosphorus is often quite low due to large leaching losses. It is in these situations that less soluble phosphorus fertilizers may have advantages in building up the soil phosphorus status (Jackson, 1966). Ozanne et al., (1961) were able to show that applying phosphorus as slightly soluble rock phosphate, increased retention of phosphorus in soil from 56 to 85 percent, but decreased plant uptake to one half that obtained if superphosphate were used. Likewise, Russell (1960 b) showed that retention of phosphorus in the top 20 cm of soil, was 89 and 75 percent respectively following application of aluminium and calcium rock phosphate. The percentage retained following superphosphate application was only 45 percent. Alston and Chin (1974) working on an acid sandy soil at Mt. Compass were also able to show advantages in using rock phosphate "...rock phosphate was as effective as superphosphate in increasing dry matter yield and phosphorus uptake by the clover in the year of application. Rock phosphate also increased yield and uptake in subsequent years, but superphosphate had little residual effect. Leaching losses of phosphorus from the top 10 cm of soil during three and a half years were equal to 100 percent and 80 percent of that applied in superphosphate at 22 and 66 kg ha⁻¹ phosphorus respectively. The corresponding losses where rock phosphate was applied were 80 percent and 60 percent."

Changing the solubility of superphosphate has also been shown to increase soil phosphorus levels in acid sandy soils (Lewis et al., 1977). Changing the ratio of water soluble to citrate soluble phosphorus in superphosphate from 21 to 0.6, increased the available soil phosphorus levels by approximately 4 ppm, seven months after applying the fertilizer.

III. Sulphur Accumulation

1. Rate of accumulation

In Australia, sulphur is usually supplied to the soil in superphosphate. In single superphosphate it is present as the anhydrite gypsum (Barrow, 1975). Other forms of sulphur, include elemental sulphur, dihydrate gypsum and pyrites. Since both pyrites and elemental sulphur are oxidizable to sulphate, it is the fate of the sulphate that determines the accumulation of sulphur in soils (McLachlan, 1975). Sulphate sulphur can either be adsorbed in the soil or transformed to organic sulphur. This conversion can be done either by plants or by some micro-organisms (Freney and Swaby, 1975). As an example of the role of micro-organisms, Freney et al., (1969) showed that when 10 ppm $\text{SO}_4\text{-S}$ was added to the soil there was steady incorporation of sulphur into organic matter over a period of 24 weeks up to a maximum of 50 percent of the added sulphur.

At any one time, the amounts of inorganic sulphur present in a soil are generally very small compared with organic forms. Therefore it is the accumulation of organic sulphur that is important to plant nutrition. Sulphur is incorporated into organic matter, along with carbon, nitrogen and phosphorus so that the ratios of these elements are reasonably constant. Williams and Steinbergs (1958) found that for a wide range of soils from eastern Australia the ratios of carbon to sulphur and nitrogen to sulphur were constant.

Barrow (1969) showed that for the Coolup sand in Western Australia, sulphur was incorporated into the organic matter at a rate of $4.4 \text{ kg ha}^{-1}\text{yr}^{-1}$.

Similarly, Hingston (1959) demonstrated that for the same soil type, total sulphur accumulated at the rate of $9.9 \text{ kg ha}^{-1}\text{yr}^{-1}$ in the top 15 cm. However, both these rates of build up represent only a fraction of that sulphur applied i.e. 25 and 30 percent respectively. In contrast to these findings, Williams and Donald (1957) showed that all the residual sulphur supplied in the superphosphate was retained in the top 10 cm of the Crockwell soil, as organic sulphur. The differences between the two soils, reflects a leaching and non-leaching environment.

New Zealand work by Walker et al., (1959) showed that the total sulphur content of soils growing pasture increased from 290 kg ha^{-1} in the virgin soil to 670 kg ha^{-1} after 25 years i.e. a rate of $15.2 \text{ kg ha}^{-1}\text{yr}^{-1}$.

2. Form of sulphur

In most soils organic sulphur is the predominant component, the soluble and adsorbed sulphate constituting only a small proportion of the total sulphur present (Walker and Adams, 1958; Freney, 1961; Nelson, 1964; Whitehead, 1964; Williams, 1967; Scott and Anderson, 1976). The organic fraction may often account for more than 90 percent of the sulphur in the soil (Evans, 1975; Scott and Anderson, 1976). Inorganic sulphur present in a soil is primarily in the form of sulphate (Freney et al., 1962; Starkey, 1966; Evans, 1975). Freney et al., (1962) found that 99 percent of the inorganic sulphur of pasture soils tested was sulphate.

(a) Organic sulphur

Sulphur in the organic form accumulates in a large range of compounds. Broadly, they can be divided into carbon bonded sulphur, as in the sulphur containing amino acids such as methionine and cystine and non carbon bonded sulphur, as in the ester sulphates (Widdowson and Hanway, 1974). Lowe and De Long (1960) found that in Quebec soils, carbon bonded sulphur accounted for 12 to 35 percent of the total sulphur

in mineral soils, as compared to 47 to 58 percent in organic soils. Similarly, Tabatabai and Bremner (1972) found that the non carbon bonded fraction comprised about 50 percent of the total sulphur in Iowa soils.

The accumulation of organic sulphur in a soil is closely correlated with carbon, nitrogen and phosphorus. Various estimates of the ratio of these four nutrients have been recorded. Walker (1957) found that under a grass-legume association in New Zealand the C:N:P:S: ratio was of the order 100:8:1.2:1. He considers that in many situations sulphur will be the limiting nutrient in the accumulation of organic matter.

(b) Inorganic sulphur

As previously mentioned over 99 percent of inorganic sulphur in soils is in the form of sulphate. Under anaerobic conditions the sulphate can be reduced to sulphide and even elemental sulphur and these compounds will accumulate (Harmsen, 1954; Hart, 1959). However, when soils are drained or dry out and become aerobic, the sulphide is oxidized back to sulphate often resulting in a lowering of pH (Hart, 1959; Starkey, 1966).

Sulphate can be present in the soil as either water soluble salts, adsorbed sulphate or insoluble sulphates (Williams, 1975). The amounts of water soluble sulphates in a soil are dependent on the soil type and rainfall. Considerable seasonal variation occurs due to the interaction of climatic conditions on the mineralization of organic sulphur, leaching of soluble sulphate and plant uptake (Harward and Reisenauer, 1966; Williams, 1967; Williams, 1968). Williams (1968) found that sulphate accumulated in the surface of the soil during summer, immediately after the senescence of the pasture. High concentrations were maintained through the summer-autumn period and then decreased to very low levels during winter and spring. Values did not fall below 3.5 ppm in the winter-spring period, and increased to over 12 ppm in the summer.

Barrow (1966) ascribes these high values over summer to the release of sulphur from soil organic matter by dessication. However, Williams (1968) suggests that this is not the main process, and that sulphate is released due to microbial decomposition of the organic matter. Lack of uptake of sulphur by plants during the summer-autumn period permits a build up.

Several insoluble sulphates are likely to be found in soils; namely barium and strontium sulphates, basic iron and aluminium sulphate and sulphate associated with calcium carbonate (Williams, 1975). The amounts of these compounds are small, and of little significance in sulphur accumulation.

Accumulation of inorganic sulphur in Australian soils is very low compared with organic sulphur. Therefore the effect of applying fertilizer to pastures over a long period is to build up the organic sulphur. The inorganic sulphur level at any one time is dependent on soil and climatic conditions.

3. Factors affecting rate of accumulation of sulphur

(a) Leaching

Unlike phosphorus, losses of sulphur due to leaching have been continually reported in the literature. Swanson and Miller (1917) were among the earliest to recognize that sulphur could be lost from cropping soils in Kansas.

Differences in the extent of sulphate movement in soils is accounted for by the variation in soil properties that affect sulphate retention (Hague and Walmsley, 1974). Increased adsorption of sulphate will occur in soils of low pH, containing hydrated iron and aluminium oxides (Nicolson, 1970). Other factors that will enhance retention and thus reduce leaching have already been discussed.

Many of the leaching studies have been performed in the laboratory

or in lysimeters. A summary of two sets of results obtained in this manner are shown in Table 6. Similarly, Hogg and Toxopeus (1966) using a laboratory leaching and incubation technique, reported leaching losses of sulphate from added superphosphate ranging from 33 to 100 percent of that applied to forty six New Zealand soils. Losses were highest from the sandy soils and pumice soils, but loamy soils were not so prone to leaching.

More meaningful results are those obtained in field experiments. Hilder (1954), working in the New England region of New South Wales, found a very low residual effect of applied sulphur and contributed this to losses of sulphur by leaching. Sulphur has also been shown to move laterally, most probably through permeable horizons (Barrow and Spencer, 1959). The largest leaching losses have been reported on the coarse textured soils and an example of the magnitude of these is shown in Table 7. Watson (1969) concluded that "...sulphur may be the limiting factor in organic matter build up on the Kojonup soils, not for the reasons which were suggested by Williams and Donald (1957), but because of the substantial loss of sulphur by leaching".

(b) Adsorption

The amount of sulphate present in a soil at any one time is largely controlled by the ability of the soil to adsorb sulphate (Barrow, 1969). Soils vary widely in their adsorption ability, from those where sulphate is not adsorbed at all (Clarke and Lewis, 1974) to those with high adsorption capacity. Barrow (1975) defines soils that will adsorb sulphate as those having surfaces with iron and aluminium atoms which are not fully co-ordinated. Also the pH has to be low enough so that the surfaces will bear a positive charge. This effect of pH on adsorption is well documented (Ensiminger, 1954; Kamprath et al., 1956; Chao et al., 1962). Barrow et al., (1969) found that for soils receiving an annual average rainfall of above 750 mm, the ability to adsorb sulphate

TABLE 6

Leaching of sulphur from lysimeters.

Soil type and location	Method	Leaching period	Sulphur supplied as	Percent sulphur leached	Reference
Hortotine sandy loam N.Z.	Soils packed in polythene cylinders.		superphosphate	3	
Mahia fine sandy loam N.Z.	Sulphur added followed by water. Leaching is followed by a drying phase. Total application 400 mm.	1 month	"	37	Hogg
Te Kopurn sand N.Z.			"	85	(1965)
Pinaki sand N.Z.			"	100	
Senhorn Clay California		12 months	gypsum	83	
"	Lysimeter (55.9 x 49.6 cm)	24 months	"	86	
"	223 mm water applied	12 months	fine sulphur	6	Jones
"	on setting up.	24 months	"	58	et al.,
Willits loam California	Rainfall in;	12 months	gypsum	56	(1968)
"	first 12 months	24 months	"	82	
"	= 623 mm;	12 months	fine sulphur	2	
"	second twelve months	24 months	"	21	
	= 1010 mm.				

TABLE 7

Leaching losses of applied sulphur from some Australian soils.

Soil type and location	Duration of trial (yr)	Depth (cm)	Sulphur applied (kg ha ⁻¹)	Sulphur leached (percent of that added)	Reference
Coolup sand, W.A.	27	0-15	896	70	
Boyanup sandy loam, W.A.	20	0-15	314	14	Hingston (1959)
Blythewood sand, W.A.	3	0-15	104	57	
		0-10	6.6	0	
Kojonup sand, W.A.	10	0-10	43	47	
		0-10	129	60	
		0-10	386	88	Watson (1969)

increased with increasing rainfall. They also noted that adsorption was greater on soils derived from basic rocks than on those from acid rocks. Similarly, the type of clay minerals are important soil factors in controlling adsorption (Kamprath et al., 1956; Neller, 1959; Chao et al., 1962).

It is concluded that sulphur accumulation will be enhanced in those soils with high adsorption characteristics.

(c) Removal by plants and animals

Plant uptake removes significant amounts of sulphur from the soil. However, under grazing, sulphur is continually cycled from soil→plant→animal→soil (May et al., 1968; Till and May, 1970 a and b; Till and May, 1971). The organic sulphur is returned to the soil in plant residues or animal excreta. As with phosphorus, removal of sulphur is much higher in hay and grain than in animal products. French et al., (1975) suggest that in 5 tonnes of clover hay, 10 kg of sulphur is removed. Likewise, 2 tonnes wheat - 4kg; 2 tonnes of oilseed rape - 14 kg; 5 kg wool - 0.2 kg; 50 kg meat - 0.4 kg and 1000 litres of milk - 0.6 kg. Similar results have been reported by Williams (1962).

(d) Form of fertilizer applied

Sulphur is most commonly applied as gypsum in superphosphate. Where additional sulphur is needed or where no superphosphate is used, the sulphur is applied most commonly as either gypsum or elemental sulphur. As previously mentioned, Donald and Williams (1954) could account for most of the sulphur applied in the Crockwell district of New South Wales, and in this situation superphosphate was quite suitable. However, sulphur does not accumulate in many of the Australian soils and less soluble sources of sulphur than those in superphosphate may have advantages. Powrie (1967) found that coarse crushed rock gypsum when used to supply sulphur to the acid sandy soils in South Australia,

was far superior to either superphosphate or fine agricultural gypsum. Diffusion of the sulphate from the coarse granule was much reduced, thus the sulphate in the soil solution was lower and leaching was reduced (Millington and Powrie, 1968).

McLachlan and De Marco (1968) found that pasture production on a black earth of the Monarco tableland in New South Wales was reduced by increasing the particle size of gypsum above 5 mm at low rates of sulphur addition. Therefore the optimum particle size for gypsum is dependent on soil type and climate.

Elemental sulphur has been shown to be superior to gypsum in maintaining a continual supply of sulphur to plants (Rhue and Kamprath, 1973; Muller and McSweeney, 1974). However, as with gypsum the size of sulphur particles is critical if a continual sulphur supply is to be available to plants (Powrie, 1967; Jones and Ruckman, 1969; Barrow, 1971). Other less soluble sulphur fertilizers include, pyrites and pyrrhotite, and these have been used as sulphur sources with varying degrees of success (Banath, 1969; Barrow, 1971).

In situations where applied soluble sulphur is prone to leaching, sulphur build up will be improved by using coarser material or less soluble sulphur fertilizers.

IV. Changes in other soil nutrients and properties

1. Nitrogen accumulation

The nitrogen levels of soils in the south east of South Australia in their native state are very low (Stephens and Donald, 1958). Values of 0.03 percent total nitrogen being very common (Taylor, 1933). From 1930 onwards, sown legumes have been used for pasture development on the poorer soils (Stephens and Donald, 1958). Initially, legumes provided an excellent source of fodder, but it was quickly realized that soil fertility was rapidly increasing as a result of legume growth. Australian agriculture has since relied on pasture legumes as a means of improving the nitrogen status of soils. This contrasts with many other

countries, where large amounts of fertilizer nitrogen are used.

Watson (1963) showed that for the Kojonup sand in Western Australia sown to subterranean clover, nitrogen accumulated in the top 10 cm at a steady rate of $47 \text{ kg ha}^{-1}\text{yr}^{-1}$ over a five year period. Similarly, Barrow (1969) found that for the Coolup sand, nitrogen build up in the top 12.5 cm was $38 \text{ kg ha}^{-1}\text{yr}^{-1}$ over a period of forty years. The build up of nitrogen under subterranean clover based pasture is enhanced by the continued use of superphosphate (Simpson, 1962; Williams, 1968). Over an 11 year period, Watson (1969) found that the nitrogen content of the soil increased at a greater rate if superphosphate was applied. However, there was no difference in nitrogen levels if the rate of superphosphate applied annually was increased from 42 to 375 kg ha^{-1} . The effect of superphosphate application on nitrogen levels in the soil is further illustrated in Table 8.

Donald and Williams (1954) concluded that there was a linear relationship between the amount of superphosphate applied and the nitrogen status of the soil. However, the results at Kybybolite and those of Watson (1969) suggest that once the initial pasture requirement for phosphorus has been met, the age of the pasture was the only factor related directly to the nitrogen status of the soil.

Although in the short term, say up to 30 years, the relationship between soil nitrogen and age of pasture curve is linear, it can be expected that this will eventually approach an asymptote (Richardson, 1938).

Data so far reviewed have resulted from work in the southern region of Australia. However, similar nitrogen accumulation has been found under tropical pastures (Vallis, 1972) and in New Zealand (Jackman, 1964).

The effect of grazing pressure on nitrogen accumulation was studied by Simpson et al., 1974. They concluded that "...high grazing pressure by sheep tended to reduce the accumulation of organic nitrogen...., but

TABLE 8

Accumulation of nitrogen in a solodized solonetz
at Kybybolite.

Depth of sampling (cm)	Total phosphorus applied (kg ha ⁻¹)	Period of superphosphate application (yr)	Nitrogen present in plots at sampling (kg ha ⁻¹)	Increase in fertilized plots over nil plots at sampling (kg N ha ⁻¹)	Rate of increase of fertilized plots over nil plots (kg N ha ⁻¹)	Reference
0-10	Nil	0	609	-	-	
10-20			279	-	-	
20-30			414	-	-	
0-10	128	14	1151	542	38.7	Cook (1939 a & b)
10-20			279	0	0	
20-30			440	26	1.9	
0-10	219	12	1151	542	45.2	
10-20			330	51	4.3	
20-30			550	110	9.2	
0-10	Nil	0	940	-	-	
10-20			400	-	-	
0-10	290	34	1769	829	24.4	Russell (1960 a)
10-20			450	50	1.5	
0-10	484	32	2085	1145	35.8	
10-20			711	311	9.7	

the effects were variable on different sections of the plots and it was uncertain ($P > 0.05$) that a real difference existed when averaged over the whole experimental area". Watson and Lapins (1964) compared the effects of three systems of pasture management on build up of soil fertility. In one system, clover herbage was returned to the soil as dung and urine, in another as dried plant material and in a third it was discarded. They could not detect changes in soil nitrogen levels due to any of the treatments.

2. Potassium accumulation

Australian soils in their native state have very marginal levels of potassium for plant growth (Stephens and Donald, 1958). The use of potassium fertilizers on pasture soils is low compared to many other countries. Therefore the increase in potassium levels in soils must be attributed to improved pasture. Williams and Donald (1957) suggest that this is brought about by "...a deeper penetration of roots by the more vigorous pasture plants, the uptake of these nutrients from lower levels, and their return to the surface soil in plant residues and animal droppings. This could also result from the greater capacity of the soil to retain cations in the exchangeable form, which, together with the decrease in pH, has led to a conversion of cations from previously non-exchangeable forms".

Accumulation of potassium can be measured as either total or exchangeable. Cook (1939 a and b) measured the build up of total potassium in a solodized solonetz at Kybybolite. He found a considerable increase in potassium in the top 30 cm of soil of all superphosphate fertilized plots. The increases were greatest in the top 10 cm. As no potassium fertilizer had been applied, he assumed the increase was a result of the process described by Williams and Donald (1957). The increase in total potassium for plots fertilized at 101 and 202 kg ha⁻¹ annually were 15.1 and 40.4 kg ha⁻¹yr⁻¹. Williams and Lipsett (1960) compared the potassium status of paddocks where the pasture had been improved to different extents. Although they noted increases in

exchangeable potassium levels, total potassium values were not significantly different.

There is considerable evidence that exchangeable potassium contents are markedly increased by pasture development (Table 9). The results of Simpson et al., (1974) would suggest that time of development is more important than the amount of superphosphate applied. Russell (1961) similarly found that the exchangeable potassium levels were unaffected by treatment.

TABLE 9

Effect of period of development on exchangeable potassium contents.

Treatment of paddock	Depth (cm)	Exchangeable potassium (m.e. 100 g ⁻¹)	Reference
Virgin Developed {Mean of 10 soils}	0-10	0.26 0.37	Williams and Donald (1957)
Unimproved pasture (Mean of 2)		0.128	Williams and Lipsett (1960)
Intermediate development (Mean of 3)	0-10	0.173	
Old pastures - 25 to 30 yr (Mean of 2)		0.557	
Superphosphate for 7 yr (27 kg P ha ⁻¹)	0-10	1.22	Simpson et al., (1974)
Superphosphate for 7 yr (244 kg P ha ⁻¹)		1.29	

Potassium can be readily leached from soils with low cation-exchange-capacity. Drover (1963) measured an annual loss of 4.5 kg ha⁻¹ potassium from lysimeters containing 60 cm of soil growing subterranean clover, receiving an annual rainfall of 465 mm. Similar losses for a siliceous sand in South Australia have been reported by Lewis et al., (1974). Accumulation of potassium will therefore be reduced in soils where leaching is a problem. Removal of potassium in farm products will also

reduce build up. As much as 10 kg of potassium can be removed in a tonne of hay (Williams, 1962).

3. Organic carbon accumulation

Since both carbon and nitrogen can be taken as indices of soil organic matter (Williams and Donald, 1957) it would be expected that organic carbon as was the case with nitrogen, would increase with time and pasture development. Russell (1960 a) found that organic carbon accumulation decreased with depth and increased with superphosphate additions over time. Similarly, Kohn et al., (1977) showed increases in organic carbon levels over a five year period. However, increasing the superphosphate dressing did not alter the accretion rate.

Watson (1969) measured organic carbon accumulation on a coarse textured sand in Western Australia. Although organic carbon levels increased over a ten year period, the rate of increase was much slower than for nitrogen.

The accumulation of organic carbon in soils is also influenced by the species grown. Rixon (1966) found that over a five year period 1132 kg ha⁻¹ of organic carbon accumulated under a clover pasture compared to 673 kg ha⁻¹ under a ryegrass pasture.

Cultivation has been shown to lower the organic carbon levels in red brown earth soils in N.S.W. (Williams and Lipsett, 1961). Organic carbon levels fell under cultivation from 1.643 percent to 1.123 percent.

4. Changes in pH

Early studies (see Leeper, 1948; Russell, 1952) have shown that pH was not affected by superphosphate dressings. However, Donald and Williams (1954) showed a relationship between soil pH and superphosphate. For every 125 kg ha⁻¹ of superphosphate applied to soils in the Crockwell district of New South Wales, soil pH decreased by 0.056. They do suggest, however, that this decline may not be due to an acidifying effect of superphosphate but to an increase in the cation exchange capacity.

Similarly, Russell (1960 a) observed a lowering of pH of the order of 0.2 - 0.3 due to superphosphate application. He also concluded that increases in cation exchange capacity were partly responsible for this decline. Watson (1969) made similar measurements in Western Australia, and in summary noted "the trend towards increasing acidity in the Kojonup soils cannot be related to the amount of superphosphate applied, but only to the age of the pasture".

5. Changes in cation exchange capacity

In fine textured soils of high cation exchange capacity, altering the organic matter content, is likely to have only minor effects on the cation exchange capacity. However, in coarse textured soils, where organic matter may have a major role in determining the cation exchange capacity, changes as a result of land and fertilizer use may drastically alter such values (Russell, 1961). Williams and Donald (1957) found that the cation exchange capacity of soils in the Crockwell district increased from an average level of 5.2 to 8.6 m.e. 100 g^{-1} in the top 10 cm as a result of subterranean clover and superphosphate. Likewise, Russell (1961) measured increases in cation exchange capacity as a result of applying different rates of superphosphate. Areas treated with two superphosphate rates, low and high, had values of 9.64 and 11.2 m.e. 100 g^{-1} respectively in the top 5 cm, compared to a value in the control area of 6.67 m.e. 100 g^{-1} . This phenomenon of increasing cation exchange capacity with phosphorus addition has also been demonstrated in other countries (Coleman and Mehlich, 1948; Sawhney, 1974).

6. Changes in C:N:P:S ratios

Walker et al., (1955) after reviewing the literature suggested that soil organic matter may have a constant C:N:P:S ratio of 100:10:1:1. However, Walker (1957) amended this figure to 125:10:1.5:1.2. This agrees reasonably well with the value Williams and Donald (1957) found for soils examined in the Crookwell district of 155:10:0.68:1.4.

Barrow (1961) disagrees with the view that all soils have characteristic ratios, and that organic phosphorus must be regarded as a variable rather than a constant fraction. Values presented in Table 10 show a range of ratios recorded in two Australian soils.

TABLE 10
A summary of C:N:P:S soil ratios

Treatment	Sample depth (cm)	Ratio of C : N : P ₀ : S			Reference	
Virgin	0-10	161	10	0.73	1.5	Williams and Donald (1957)
Fertilized pasture		153	10	0.66	1.4	
Coolup sand	- virgin	238	10	0.85	2.1	
	- pasture	131	10	0.85	1.5	
Boyanup sandy loam	- virgin	169	10	0.65	1.6	Hingston, (1959)
	- pasture	140	10	0.55	1.8	
Blythewood sand	- virgin	232	10	0.68	1.6	
	- pasture	210	10	0.97	1.6	

The ratio of nitrogen to sulphur in general shows less variation than carbon to sulphur (Scott and Anderson, 1976). This is also shown in the data presented in Table 10.

SELECTION OF SITES AND
SAMPLING TECHNIQUE

I. Location

The south east of South Australia has a rather unique physiography. A series of low ranges, with intervening plains, occurs more or less parallel to the present coastline. These low ranges represent old coastal dunes or dune remnants stranded during a retreat of the sea (Tiver and Crocker, 1951). This simple pattern was complicated by large drifts of sand which occurred during an arid period, probably less than 3000 years ago (Coaldrake, 1951). This has resulted in large areas of siliceous sand country extending over the whole South East.

In selecting areas where nutrient accumulation would be measured, the first consideration was similarity in soil type. By studying reports by Taylor (1933), Coaldrake (1951), Blackburn et al., (1953) and Blackburn (1959 and 1964) and using local knowledge of the region, three areas were chosen that consisted of very similar soils. These were the Hundreds of Coles, Willalooka and Senior, the location of which are shown in Figure 1. The fact that these areas received varying mean average rainfalls was also a factor considered when choosing them. Also similarities in vegetation, time of development and agricultural practices were all considered in making the final choice of Hundreds.

1. Coles

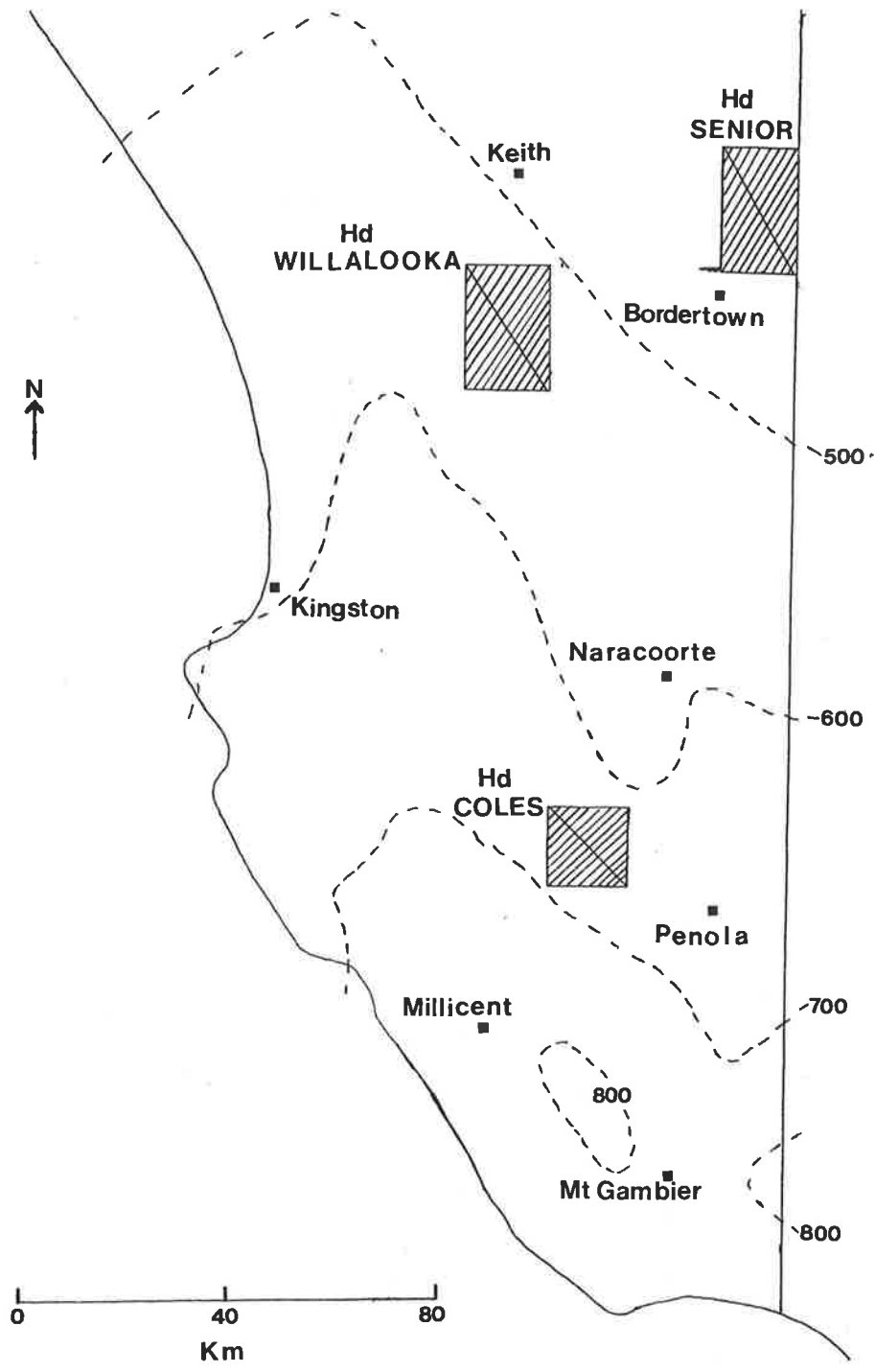
The soils consist of podzols, solodized solonetz with small areas of terra rossa. The topography of the area is sand plains with occasional sand banks with many swampy parts (Blackburn, 1964). The native vegetation consists predominantly of *Eucalyptus baxteri*, *Eucalyptus fasciculosa*, *Eucalyptus leucoxydon*, heath and rushy swamps. Average rainfall for the area is 650 mm.

2. Willalooka

The soils consist primarily of sands and solodized solonetz. Taylor (1933) designated three main soil types namely, Laffer, Willalooka

FIGURE 1

Location of the three Hundreds and mean annual
rainfall isohytes (mm) for the South East of South
Australia.



and Monkoora sands. Differences between the three types are in surface colour of sand, depth of sand to clay and presence or not of an underlying limestone. The region may be divided into three zones, hill country, plain country and swampy flats. The plain country is the dominant unit occupying some 58 percent of the land surface (Taylor, 1933). Vegetation in the area contains, *Eucalyptus diversifolia*, *Eucalyptus incrassata*, *Melaleuca* species, *Hakea rugosa*, heath plants and small tea-tree as the dominant species. Average rainfall for the area is approximately 525 mm.

3. Senior

As with the other two areas the soils are mainly sands and solodized solonetz, and can be divided into two main phases; Buckingham sand and Shaugh sand (Coaldrake, 1951; Blackburn et al., 1953; Blackburn, 1959). Sand plains are the dominant topographical unit, with some sand rises and swampy areas. *Eucalyptus fasciculosa*, *Eucalyptus incrassata*, *Melaleuca uncinata*, *Melaleuca pubescens* and heath are the dominant species. Rainfall for the area is 400 mm.

II. Materials and methods

1. Procedure for selecting sampling sites

(a) Survey

Initially a simple questionnaire (see Appendix 1) was sent to each farmer in the Hundred, accompanied by a letter explaining the purpose of the work. The questionnaire was designed so that information about individual paddocks on the property could be obtained relating to; time since clearing; superphosphate history; cropping history; soil type; pasture composition and stocking intensity. Following the letter, a visit was made to each farmer, to help him fill in the questionnaire and to gain personal impressions about the property. The survey for the Hundred of Coles was conducted in 1974, and Hundreds of Willalooka and Senior in 1975.

(b) Treatment of survey data

Data collected from each property were tabulated under the following headings; soil type, area cleared, superphosphate applied, stocking rate and age of individual paddocks. From these figures, properties were rejected if the records relating to these parameters were incomplete. The second criterion for excluding properties was soil type. It was decided that measurements would be made on soils with a depth of sand over clay ranging from 30-90 cm. This depth of soil allowed for the movement of nutrients down the profile to a rather impermeable clay layer. Therefore, properties containing none or very little of this soil type were rejected. Another exclusion criterion was the use of excessive or minimal amounts of superphosphate. Either extreme would certainly affect the accumulation of nutrients. The final rejection criterion was overcropping, since nutrient mineralization and hence accretion of organic matter is affected by soil cultivation.

After consultation with statistical advisers, it was decided that 30 paddocks would be selected from the remaining properties for each Hundred. This number would provide both a range of paddock ages i.e. from virgin scrub up to 25 years of pasture and provide enough points for regression analysis. Even though only 30 paddocks were needed for each Hundred, some 45 paddocks were selected from the survey data, so that a choice could be made of the more suitable paddocks in the field.

2. Sampling technique

The chosen paddocks were inspected and a site 100 x 100 m selected with suitable soil type, pasture composition and position in the paddock. Precautions were taken not to select sites near fences or trees as uneven fertilizer spreading is likely near these points. Efforts were made to select a site that supported a pasture similar

to the whole paddock. In selecting the sites the range in depth of sand over clay was narrowed to 40-60 cm. This was thought to be one way of reducing variability.

Within the 100 x 100 m area ten points were located, around which three independent soil samplers each collected soil samples at depths from 0-10 cm, 10-30 cm, 30 cm - clay and 0 - 7.5 cm of clay. The depth to clay was noted for each hole. Samples collected at each depth from the ten points were bulked. A 5 cm Jarret auger was used to collect samples. Bulk density measurements were made at each site using a double tube soil sampler of 3.1 cm internal diameter. Soil samples were air dried, passed through a 2 mm sieve and stored in sealed containers for future analysis.

The major soil sample collection and pasture observations were made for Coles from the 24th November to 11th December, 1974; for Willalooka from the 6th October to the 6th November, 1975 and for Senior from the 27th August to the 18th September, 1975. Additional soil samples (0-10 cm) were taken using a double tube soil sampler in the autumn of the following year. These samples were used to compare changes in available soil phosphorus.

Measurements of pasture composition and dry matter present at the time of sampling were made by visually rating what was in the paddock and calibrating these observations with cut quadrats that were firstly estimated and then sorted into species and weighed.

III. Results and discussion

1. Survey data

The overall response from the farming community to the questionnaire and subsequent survey was excellent. Farmers in general were eager to obtain information that would help them make decisions on fertilizer requirements, as fertilizers constitute one of their largest expenses.

The timing of the survey coincided with an increase in the price of superphosphate, due in part to the removal of the superphosphate bounty in December, 1974. Also at this time, financial returns from livestock products were declining, as a result of very low cattle prices. Thus farmers had less money to spend and required information on how to get the best return for the money invested in fertilizers.

All farmers approached in the Hundred of Coles were willing to provide all information possible. Data were not collected from four properties, due to the landholders not living on the farm, or the property changing ownership at the time.

The survey conducted in the Hundred of Willalooka was affected by an outbreak of footrot in the area. Two property owners declined to take part in the survey due specifically to the risk of footrot being introduced onto their property. Special care was taken to sterilize the vehicle after leaving each property when conducting the survey and collecting the soil samples. Three other properties were not included due to absentee landholders.

Only two properties were not included in the Hundred of Senior survey, both as the result of absentee landholders. Approximately a third of the land in this area was owned by one company, i.e. property 17.

A summary of the data collected from the three regions is shown in Table 11. Detailed information from each property in the region is given in Appendix 2, while the localities of properties in the Hundreds are shown in Figures 2,3 and 4.

Although very little land development in the regions commenced before 1950, nearly ninety percent of all land is now cleared and sown to pastures (Table 11). Large areas in the Hundreds of Senior and Willalooka were developed in the early 1950's by the Australian Mutual Provident Company. Similarly, the War Service-Land Settlement Scheme which commenced in 1946 accounted for much of the development:

FIGURE 2

Location of farm properties, Hundred of Coles.

HD COLES

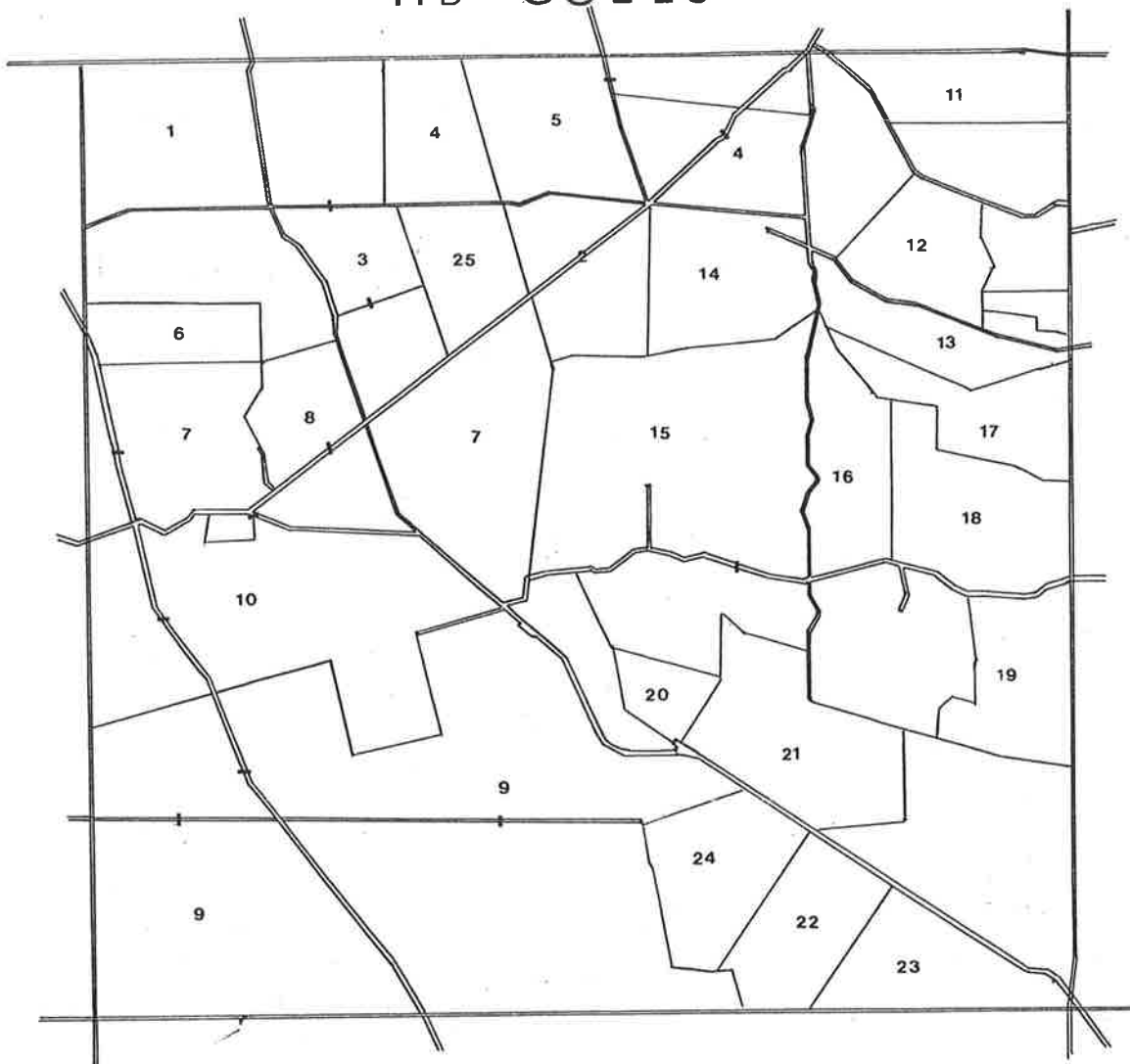


FIGURE 3

Location of farm properties, Hundred of Willalooka.

HD WILLALOOKA

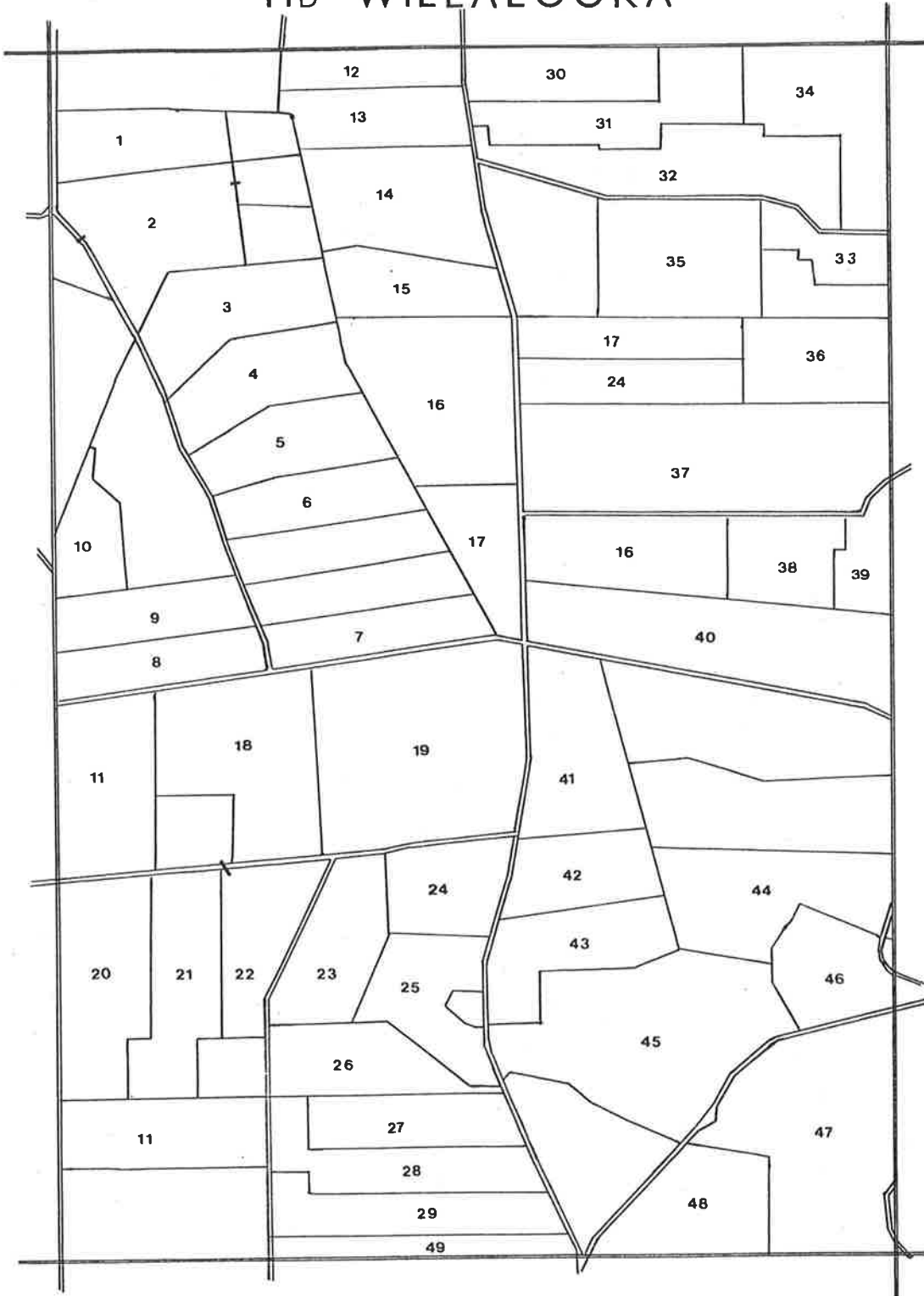


FIGURE 4

Location of farm properties, Hundred of Senior.

HD SENIOR

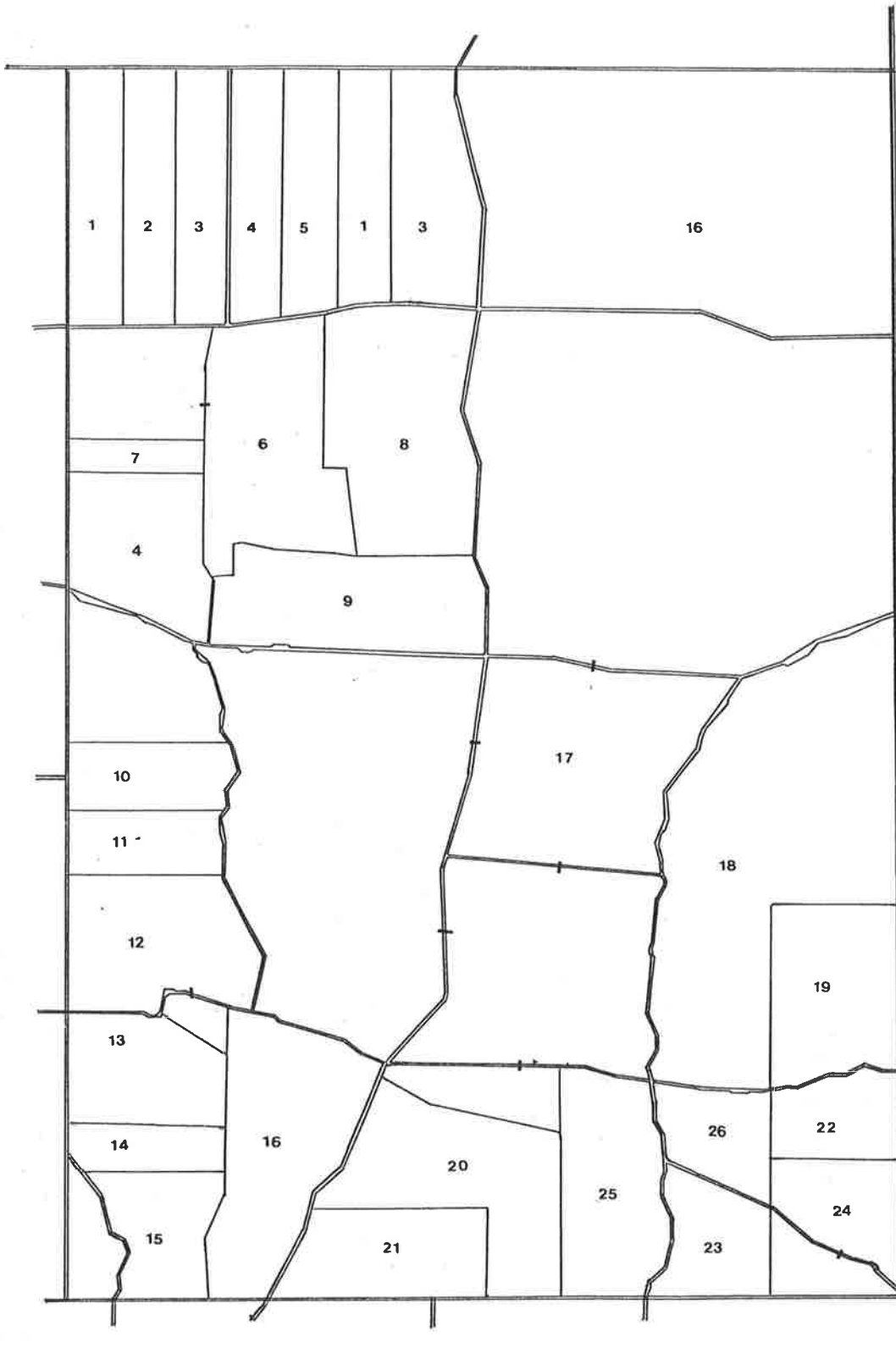


TABLE 11

Summary of survey data collected from Hundreds of Coles, Willalooka and Senior.

Hundred	Number of properties in survey.	Total area of land in survey (ha)	Land cleared (percent)	Soil type (percent)			Super-phosphate average annually (kg ha ⁻¹)	+Stocking rate (D.S.E ha ⁻¹)	
				Heavy sand*	Shallow sand*	Med.*Deep sand			
Coles	25	23,956	84	10	44	34	12	182	8.4
Willalooka	49	30,855	90	15	39	37	9	135	8.1
Senior	26	34,156	92	15	34	34	17	109	5.9

* Shallow sand < 30 cm

Medium sand 30-90 cm

Deep sand > 90 cm

+ Stocking rate determined on farm basis and not on a total area basis.

in the Hundred of Coles. Companies and large land holders from other areas of the State have also been responsible for developing extensive areas, e.g. property 17, Hd. Senior and property 9, Hd. Coles.

The soil types of the three regions are very similar as shown in Table 11. The areas of medium sand, i.e. 30-90 cm of sand over clay, in each Hundred are approximately equal.

Average superphosphate dressings applied annually to the areas since development increase from 109 kg ha⁻¹ for Senior to 182 kg ha⁻¹ for Coles. Variation between years in superphosphate applications are shown in Table 12. Superphosphate useage in all areas increased steadily up until and including 1974. This was due in part to very good returns from livestock production. The advent of depressed markets and increases in the price of superphosphate are reflected in superphosphate use in

TABLE 12

Superphosphate applied to the regions in the period 1971-75

Hundred	Average superphosphate applied (kg ha ⁻¹ yr ⁻¹)				
	1971	1972	1973	1974	1975
Coles	139	146	184	234	n.d.*
Willalooka	n.d.	112	126	160	60
Senior	n.d.	97	103	113	39

*n.d. not determined.

1975, i.e. for Senior the average fell from 113 kg ha⁻¹yr⁻¹ in 1974 to 39 kg ha⁻¹yr⁻¹ in 1975.

Suprisingly, the stocking rates for Hundreds of Coles and Willalooka are very similar i.e. 8.4 and 8.1 D.S.E. ha⁻¹ respectively. It would have been expected from average annual rainfall figures, that the stocking rate in the Hundred of Coles would be considerably higher. It is thought that two factors, namely, size of holdings and areas of land under water during certain periods of the year, may influence this finding. In general, it was found that the larger properties had lower stocking rates (Appendix 2). This is due most likely to better management practices on the smaller holdings. The average property size for Willalooka was 630 ha, compared with 958 ha for Coles. Also early spring growth is often limited in the Coles region due to large areas of pasture becoming waterlogged and often being submerged by water (Blackburn, 1964). Stocking rate in the Senior area was much lower, i.e. 5.9 D.S.E. ha⁻¹, due primarily to reduced rainfall, and perhaps larger holdings.

2. Selection of sites

Before any paddocks were chosen, certain farms in each area were excluded. The properties and the reasons for excluding them are given in Table 13.

TABLE 13

Properties excluded and reasons for doing so.

Reason for excluding property	Property number		
	Coles	Willalooka	Senior
Low superphosphate application	6	11,37	
High superphosphate application		48	
Unsuitable soil type	11,12	8,9,10,12,27, 28,36,46	
Incomplete records	18,21	5,6,7,10,13, 34,37,38,41	4,7,10, 11,23
Excessive cropping			1,3
Footrot		4,45	

Of those farms remaining, a range of paddocks with various ages of pasture were chosen before going into the field. The paddocks were chosen, firstly to give a range of pasture ages and secondly to include as many properties as possible. The 30 sites selected for each Hundred are shown in Tables 14,15 and 16. Three undeveloped sites were selected in each area.

Superphosphate applied to paddocks was where possible the exact amount spread on that paddock. Where it was not possible to obtain this information for paddocks, the average farm rate was multiplied by the years since development.

Two paddocks that had been developed for more than 25 years were initially selected and soil samples collected, i.e. site 9, Hundred Coles and site 19, Hd. Senior. However, both were excluded from regression analysis of the data, on statistical advice. Results from one other

site, namely, site 27, Hd. Willalooka, were also excluded from analysis. This was due to the site having been cleared for only three years, but before this period being used as a stock holding area. Thus accumulation of nutrients was much higher than would be expected under a three year old pasture.

Pasture data collected for all sites at the time of soil sampling are shown in Tables 14,15 and 16. Because of differences in time when the data were collected it is difficult to make comparisons between Hundreds. No lucerne was recorded at any of the sites in Coles. However, 12 and 14 of the sites in Willalooka and Senior respectively (Tables 15 and 16) contained some lucerne in the pastures. The invasion by annual grass and fog grass species into the pastures can be directly related to the age of the pasture. Relationships found for the three areas were:

$$\text{Coles} \quad \text{Fog grass \%} = 11.4 + 1.22x \quad ** \quad (100 r^2 = 32)$$

$$\text{Willalooka} \quad \text{Annual grass \%} = 18.0 + 1.91x \quad *** \quad (100 r^2 = 40)$$

$$\text{Senior} \quad \text{Annual grass \%} = 6.0 + 1.85x \quad *** \quad (100 r^2 = 62)$$

(where x = age of pasture in years).

The best correlation was found in Senior, and the worst in Coles. This could be due to the lower rainfall in the most northern site, resulting in less favourable conditions for sown annual species. These sown species are subsequently replaced by annual grass species with time. This theory is supported by the much lower clover component in Senior compared to both Willalooka and Coles.

TABLE 14
Site characteristics; Hundred of Coles

Site No.	Property on which site chosen	Years since development	Superphosphate applied (kg ha ⁻¹)	Pasture present at time of sampling (kg ha ⁻¹ D.M.)	Pasture species (percent)					Depth to clay (cm)
					Perennial grass	Fog grass	Sub. clover	Straw. clover	Misc.	
1	3	12	2508	6000		60	20	20		54
2	3	8	1672	5000		35	15	40	10	53
3	23	0	0	-						57
4	23	6	1254	2500	15	30	15	5	35	57
5	1	18	3366	5000		60	15	20	5	51
6	1	11	2057	3000		30	30	30	10	49
7	1	0	0	-						49
8	9	25	4200	4000		40	5	40	15	51
9	9	45	7056	4500		70	25		5	44
10	9	9	1512	2500	5	35		40	20	54
11	10	2	336	4000	60		25	10	5	50
12	25	7	1163	5000	40		30	20	10	52
13	25	9	1881	3000	25		15	30	30	46
14	15	23	3611	3000		20	40	10	30	46
15	15	19	2983	3000	15	15	35		35	46
16	15	2	314	2500	55		15	25	5	50
17	15	5	785	3000		50	30	5	15	53
18	15	16	2512	4000		40	25		35	52
19	16	0	0	-						55
20	16	21	3990	5500	25	25	10	25	15	49
21	16	12	2280	4000	15	40	25	10	10	49
22	13	19	2983	3000	30	15	20		35	48
23	13	7	1099	4000	60	25	10		5	51
24	7	12	2148	5500	25	30	10	5	30	53
25	7	17	3043	1500	60	5	15	5	15	59
26	22	6	1254	4500	35	35	5	15	10	54
27	24	8	1256	2000	5	15	5	20	55	50
28	9	21	3528	2500	5	35	20	5	35	54
29	5	5	1045	2000	30	15	10	35	10	54
30	19	15	2520	6500	5	55	30		10	58

TABLE 15

Site characteristics; Hundred of Willalooka

Site No.	Property on which site chosen	Years since development	Superphosphate applied (kg ha ⁻¹)	Pasture present at time of sampling (kg ha ⁻¹ D.M.)	Pasture species (percent)					Depth to clay (cm)
					Perennial grass	Lucerne	Sub. clover	Annual grasses	Misc..	
1	42	20	2080	2000	5		5	55	35	50
2	16	14	1568	2500	20		15	55	10	44
3	16	18	2016	2000	5	20	10	50	15	49
4	19	0	0	-						50
5	19	11	1727	3000	15		30	30	25	49
6	25	22	2948	2500	20		45	25	10	45
7	32	9	1125	2500	5	5	45	40	5	50
8	32	10	1250	2500	5	5	25	50	15	51
9	22	2	224	500	50		40		10	41
10	23	18	2016	3000	5	20	20	40	15	51
11	23	20	2240	2000	10		30	50	10	53
12	35	12	1500	2500	15		20	60	5	50
13	40	7	875	2000	5	35	5	55		50
14	18	13	1625	1250			35	60	5	51
15	18	0	0	-						55
16	19	25	3925	2500			20	70	10	46
17	26	23	2829	2500	10		15	70	5	49
18	19	4	628	3000	86		10		5	43
19	47	3	627	2500	30	10	25	35		51
20	47	6	1254	2000	30	30	10	25	5	46
21	47	13	2717	3500	5	30	5	55	5	50
22	44	10	2090	3500		25	5	65	5	49
23	44	1	209	3500	5	20	70		5	51
24	44	0	0	-						52
25	14	24	3000	1250	15		20	30	35	45
26	20	23	3082	2000	15		25	50	10	42
27	31	3	375	3000		35	10	50	5	47
28	2	10	1340	3000	5	10	15	65	5	47
29	1	22	2464	2500	10		25	60	5	48
30	35	16	2000	3000			15	80	5	47

TABLE 16
Site characteristics; Hundred of Senior

Site No.	Property on which site chosen	Years since development	Superphosphate applied (kg ha ⁻¹)	Pasture present at time of sampling (kg ha ⁻¹ D.M.)	Pasture species (percent)					Depth to clay (cm)
					Perennial grass	Lucerne	Sub. clover	Annual grasses	Misc.	
1	17	10	1480	500	20	5		40	35	46
2	17	17	1564	800			20	65	15	54
3	17	9	1350	800	5	5	35	35	20	57
4	17	18	1476	700	40		5	20	35	52
5	17	2	414	3000	10	30	40	15		54
6	17	4	864	800	45	40			15	51
7	17	6	1188	1000	50	30		15	5	53
8	17	15	1650	1500	45		5	45	5	51
9	17	13	1586	600	40	15	5	30	10	52
10	17	8	1312	1000	30	35		20	15	46
11	8	0	0	-						50
12	16	19	1976	4500	60			40		52
13	16	11	1144	1500	10	50	5	20	5	53
14	13	0	0	-						50
15	6	23	2852	500	35		5	30	30	56
16	6	22	2728	1000	60		5	25	10	51
17	2	21	2499	2000	15	15	5	60	5	54
18	25	20	2500	1750	35		5	40	20	47
19	25	30	3750	1000			5	60	35	56
20	12	2	418	3000	20	60			20	48
21	12	22	1364	1500	40			40	20	47
22	24	12	1248	1500	20	30	5	25	20	50
23	19	13	1352	750	15		20	40	25	50
24	19	7	728	1000	45		10	30	15	54
25	21	23	2323	1500	30			65	5	47
26	9	1	209	3000	5	35	50	5	5	50
27	9	18	1116	2000	50		15	30	5	50
28	5	7	938	2500		50		40	10	55
29	18	5	1045	3000	30	40	10	10	10	50
30	18	0	0	-						47

ACCUMULATION OF NUTRIENTS
AND CHANGES IN SOME
SOIL PROPERTIES

I. Materials and methods

1. Soil analysis

(a) Total phosphorus, sulphur, potassium and calcium

Soil samples were ground to a fine powder by milling for 3 min in aseib-technik mill. This procedure reduced sub sampling errors by ensuring thorough mixing of both organic and inorganic soil components. Samples were then incorporated with boric acid in a disc that was used for measurements of total phosphorus, sulphur, potassium and calcium by X-ray spectroscopy. Three measurements of "line and background" were made and an average taken. Phosphorus and sulphur were determined for all soil samples collected, i.e., 0-10 cm, 10-30 cm, 30 cm-clay and clay. Calcium and potassium were determined for the top 10 cm layer only. Values were reported in ppm. Amounts of phosphorus and sulphur in kg ha⁻¹ were computed from these figures, taking into consideration variations in bulk density and depths of the different soil layers.

(b) Total nitrogen

Total nitrogen was determined by a modified Kjeldahl method (Bremner, 1965). To a large test tube, 1 g of finely ground soil (0-10 cm) and 1 cm³ of distilled water was added and allowed to stand for 15 min. 2.5 cm³ of concentrated sulphuric acid was added and a small funnel placed in the top of the test tube. The test tubes were then placed in an aluminium block on top of a hot plate. Heating continued until white fumes appeared. 1 g of catalyst (K₂SO₄, CuSO₄ and Se) was added and heating continued for a further 3 hr. On cooling, the contents were diluted to 50 cm³ with distilled water. A 30 cm³ aliquot of this was poured off and used for analysis on the auto analyser. Nitrogen as ammonium sulphate was measured by developing colour with alkaline phenate/sodium hypochlorite in the auto analyser (Auto Analyser Methology Industrial Method 18-69W).

(c) Organic phosphorus

Using extraction methods, organic phosphorus was determined by difference between total phosphorus and inorganic phosphorus. The method used, followed that proposed by Steward and Oades (1972) with the exception that the ultrasonic vibration step was replaced with a 16 hr shaking. After extraction with HCl - NaOH, total phosphorus was measured after perchloric acid digestion by Usher's adaption (Usher, 1963) of the method outlined by Bartlett (1959).

Inorganic phosphorus was determined by the methods of Murphy and Riley (1962) and John (1970) after the humic materials were precipitated with 5 and 10 cm³ aliquots of 0.05 M H₂SO₄ respectively. The supernatant fraction was neutralized with 3M NaOH.

Organic phosphorus values were calculated for the 0-10 cm and 10-30 cm depths.

(d) Available phosphorus

Available soil phosphorus was determined on air dried soil samples (0-10 cm) collected in spring and autumn using Bray's No. I reagent (Bray and Kurtz, 1945). To 5 g of soil, 50 cm³ of a 0.03M NH₄F and 0.025M HCl solution was added and shaken for 1 hr on an end over end shaker. After filtration, the extract was stored for analysis on the auto analyser. Colour development was achieved with ammonium molybdate and stannous chloride.

The use of Bray's I was preferred to Olsens extractant (0.5M NaHCO₃) because there was less interference in colour development caused by extracted organic materials.

(e) pH

Soil pH was determined on soil samples collected from all depths. A suspension of 10 g of soil and 50 cm³ of water was shaken for 15 min on an end over end shaker. After standing for a further 15 min pH measurements were made with an Eel pH radiometer and a hydrogen electrode.

(f) Cation exchange capacity and exchangeable cations

To a plastic bottle containing 5 g of soil, 35 cm³ of M NH₄Cl was added and shaken for 10 min. After centrifuging at 3000 rpm for 10 min the supernatant fraction was filtered and the filtrate collected. The addition of NH₄Cl and subsequent steps were repeated three times. All filtrates were collected, made to volume and stored for exchangeable cation analysis.

After the cations were extracted by the above method, the NH₄ saturated soil was extracted with a solution of M KNO₃ and 0.25 M Ca(NO₃)₂. Free NH₃, NH₄⁺ and NH₄⁺ bound to the exchange sites were determined by an alkaline phenate method on the auto analyser. Free chloride ions were also determined on the auto analyser using a ferric thiocyanate method. The cation exchange capacity was determined by difference.

Exchangeable cations, potassium, magnesium and calcium were determined by atomic absorption spectroscopy. A suppressing agent, strontium chloride was used to overcome interference due to phosphate, aluminium, silicate and sulphate in the analysis of calcium and magnesium. Soil samples collected from the 0-10 and 10-30 cm depths were analysed and the results expressed as m.e. 100 g⁻¹ of soil.

(g) Organic carbon

Organic carbon contents in the 0-10 cm and 10-30 cm layers were determined by the Walkley and Black rapid titration method (Walkley and Black, 1934). Values obtained were expressed as percent organic carbon.

(h) 'Active' iron

To determine 'active' iron peroxidized soil was shaken for 2 hr with a mixture of 0.2M ammonium oxalate and 0.2M oxalic acid at pH 3; the iron in solution was measured by the method of Sandell (1959). Measurements were made only on the 0-10 cm samples collected from virgin sites for each Hundred.

2. Statistical analysis of the results

Data collected were compared by regression analysis using version 6.50 of the 'Statistical package for the Social Sciences'. Both linear and quadratic curves were fitted to all data. Two independent variables were used, namely years since clearing and superphosphate applied (kg ha^{-1}). Results were expressed as:

$$\text{Dependent Variable (y)} = \text{Const.} + b \text{ (Independent variable)}$$

or

$$\text{Dependent Variable (y)} = \text{Const} + b_1 \text{ (Independent variable)} + b_2 \text{ (Independent variable)}^2$$

The variation accounted for is expressed as $100r^2$, and the significance of the relationship expressed as:

$$< 0.05 \quad *$$

$$< 0.01 \quad **$$

$$< 0.001 \quad ***$$

Certain data, e.g. C:N:P:S ratios could not be treated in the above manner. Instead an asymptotic regression line was fitted using the relationship;

$$Y = A + B r^x$$

where Y = dependent variable

A = constant

B = slope

r = power

X = superphosphate applied kg ha^{-1} or years since clearing.

This equation was further transformed into the form: -

$$Y = A + B e^{-CX}$$

II. Results and discussion

1. Phosphorus accumulation

(a) Total phosphorus

Total phosphorus accumulation was greatest in the top 10 cm for all three areas. However, phosphorus levels in the 10-30 cm and 30 cm - clay

layers did increase with time (Figs. 5, 6 & 7). The magnitude of this accumulation is seen more easily in Table 17, where levels in the virgin soil are compared with those after twenty five years of pasture. There was no change in the phosphorus levels in 0 - 7.5 cm clay layer for any of the three Hundreds.

TABLE 17

Hundred	Depth (cm)	Total Phosphorus (ppm)		
		Virgin	After 25 yr of development	Increase in P ppm
Coles	0-10	52	119	67
	10-30	30	41	11
	30-clay	32	54	22
Willalooka	0-10	38	126	88
	10-30	30	51	21
	30-clay	30	45	15
Senior	0-10	48	119	71
	10-30	31	51	20
	30-clay	27	44	17

Accumulation of total phosphorus in the 0-10 cm layer has occurred at the lowest rate in Coles and the highest in Willalooka (Table 17). A greater accretion rate of total phosphorus has occurred in the 30 cm-clay than 10-30 cm layer in the Coles Hundred. This suggests that phosphorus is moving down the profile. However, accumulation in the 30 cm - clay layers were seen in all three regions. Therefore, these soils are quite different from those looked at by Donald and Williams (1954) where all the applied phosphorus could be accounted for in the surface 10 cm of soil, but are similar in many respects to those studied by Hingston (1959); Russell (1960 b); Ozanne et al., (1961) and Alston and Chin (1974).

Superphosphate applications in the three localities were 182, 135 and 109 kg ha⁻¹ for Coles, Willalooka and Senior respectively. However,

FIGURE 5

Accumulation of total soil phosphorus (ppm) as related to years since clearing, for three soil depths, Hundred of Coles.

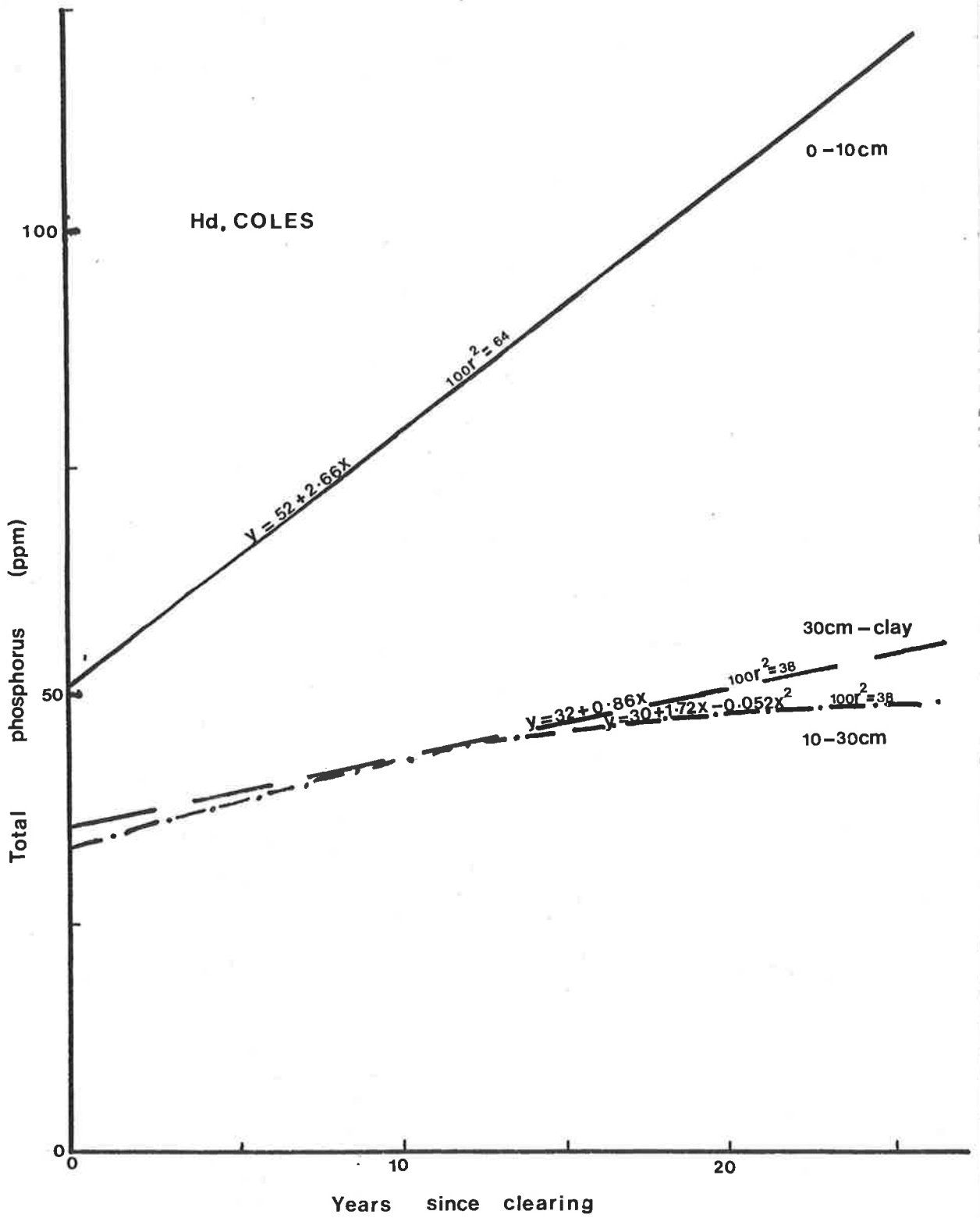


FIGURE 6

Accumulation of total soil phosphorus (ppm) as related to years since clearing for three soil depths, Hundred of Willalooka.

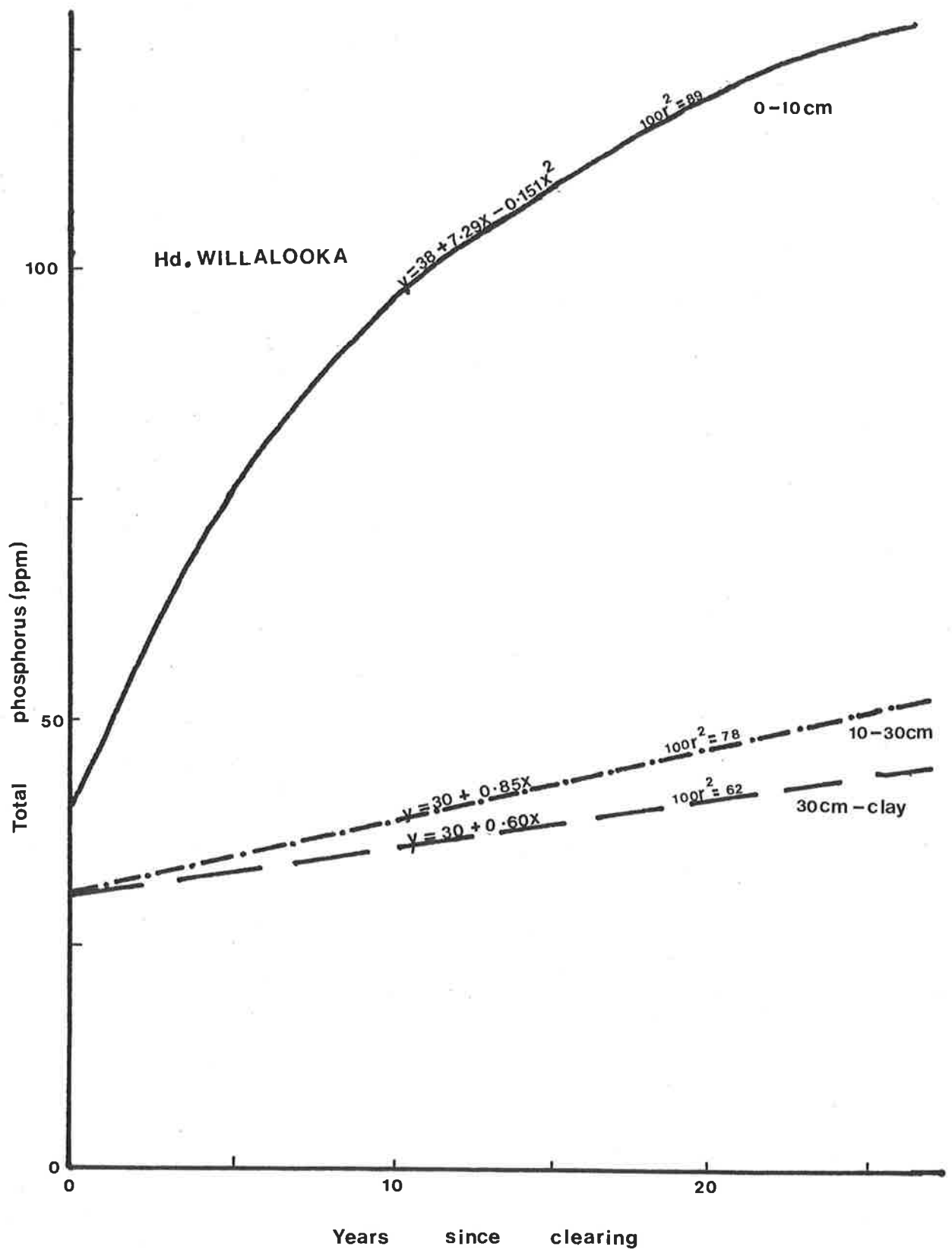
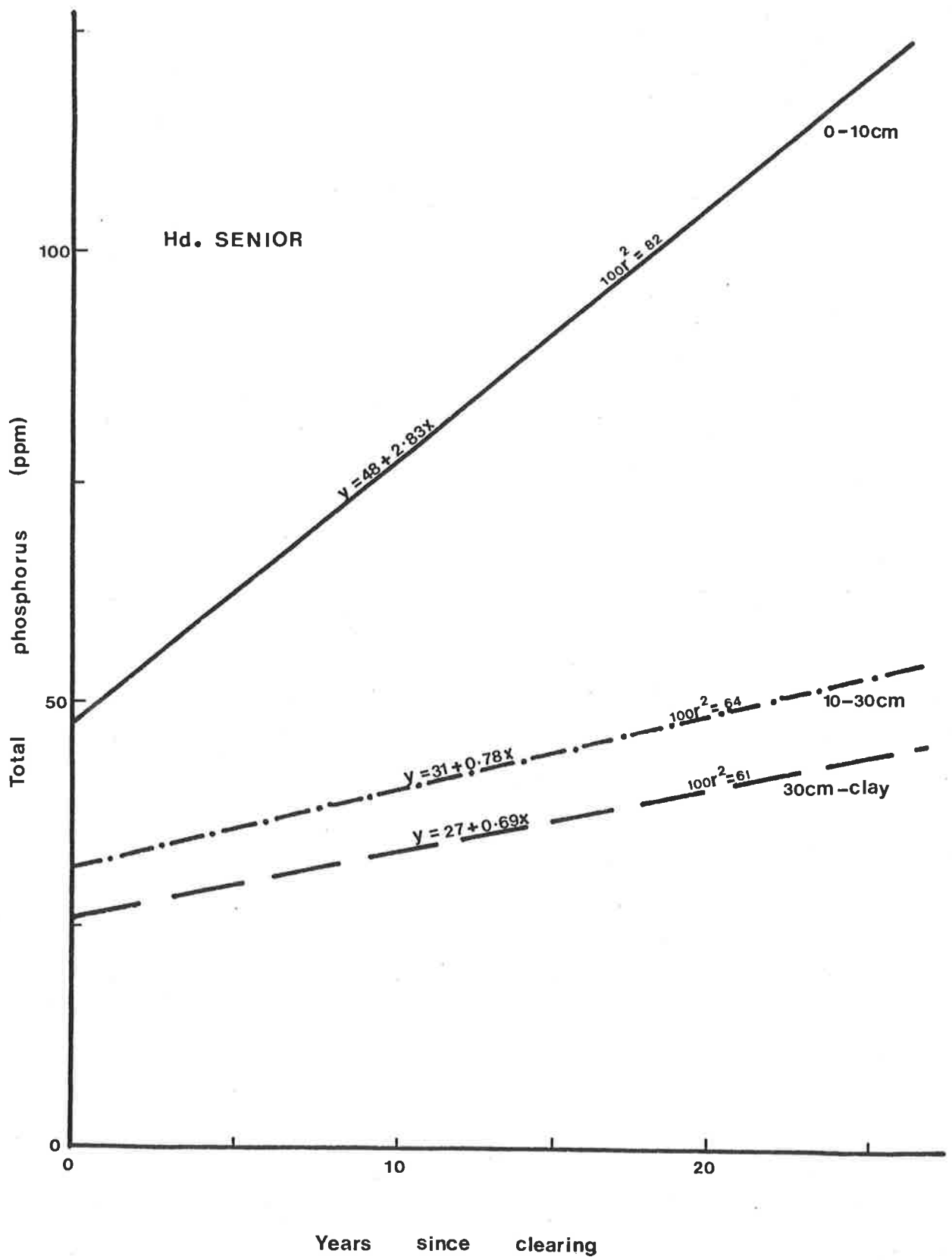


FIGURE 7

Accumulation of total soil phosphorus (ppm) as related to years since clearing for three soil depths, Hundred of Senior.



the substituting of superphosphate applied for years since clearing did not greatly improve the significance of the relationships for phosphorus accumulation in 0-10 cm layer. The relationships are:

$$\text{Coles} \quad \text{Total phosphorus (ppm)} = 49 + 0.017x^{***} \quad (100r^2=71)$$

$$\text{Willalooka} \quad \text{Total phosphorus (ppm)} = 38 + 0.051x - 0.0000068x^2^{***} \quad (100r^2=88)$$

$$\text{Senior} \quad \text{Total phosphorus (ppm)} = 44 + 0.028x^{***} \quad (100r^2=81)$$

(where x = superphosphate applied kg ; ha⁻¹)

To measure the actual fate of applied phosphorus it is necessary to look at accumulation of phosphorus expressed as kg ha⁻¹. In Figures 8 and 9 the build up of phosphorus (kg ha⁻¹) is plotted against years since clearing and superphosphate applied. All relationships for the 0-10 cm layers are linear, suggesting that both inorganic and organic fixation have not declined with superphosphate application. For every 100 kg ha⁻¹ of superphosphate applied, 3.4, 3.2 and 2.0 kg ha⁻¹ phosphorus accumulate in the 0-10 cm layer, in the Hundreds of Senior, Willalooka and Coles respectively. Once again the Coles region shows the poorest retention of applied phosphorus, with little difference between the two northern Hundreds.

Phosphorus accumulation in the 10-30 cm layer was similar for all areas (Fig. 9). The relationship for the Coles region is quadratic, suggesting that in this layer retention of phosphorus was greater in the earlier years of development. With continual superphosphate applications, more and more of the phosphorus passed through this layer to lower depths. This fact is illustrated in Table 17. However, the amounts of phosphorus accumulating in 10-30 cm depth were significant. For the Senior and Willalooka areas, phosphorus has accumulated at the rate of 2.0 and 1.7 kg P ha⁻¹ for every 100 kg ha⁻¹ of superphosphate applied. This differs from the findings of Ozanne et al., (1961) who found no marked

FIGURE 8

Accumulation of total phosphorus (kg ha^{-1}) in the
0-10 cm soil layer as related to years since
clearing and superphosphate applied (kg ha^{-1}), Hundreds
of Coles, Willalooka and Senior.

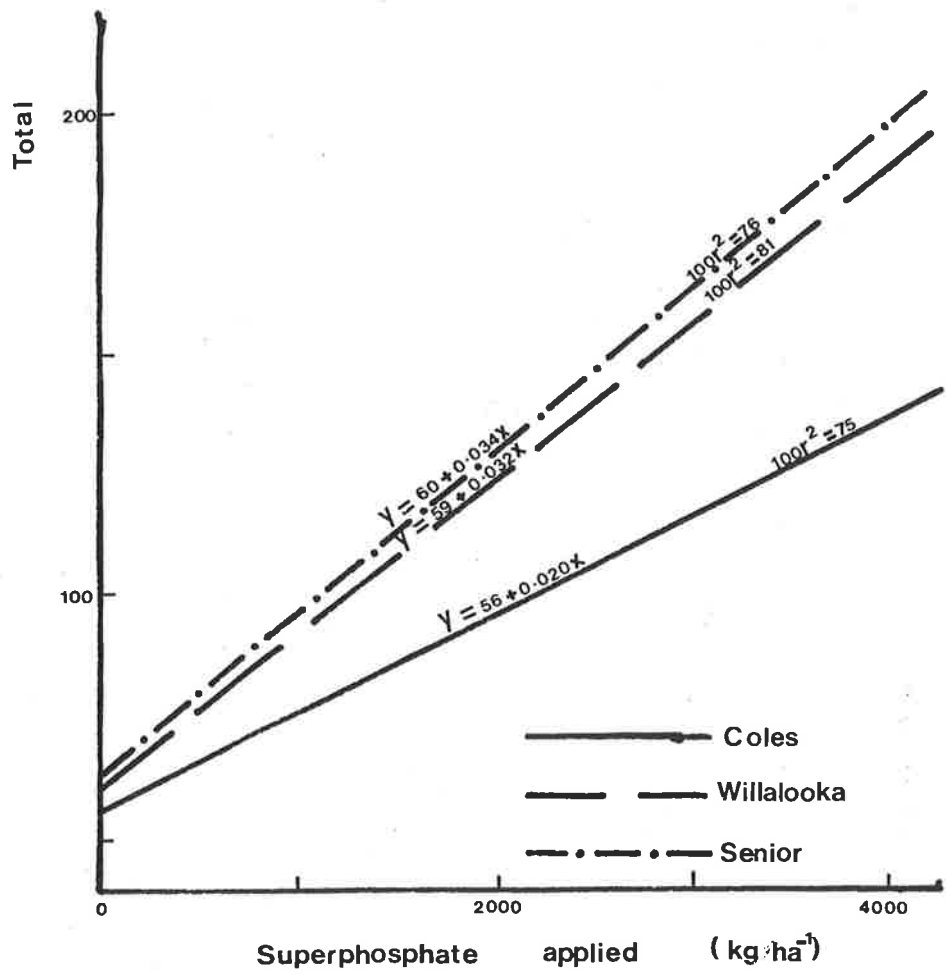
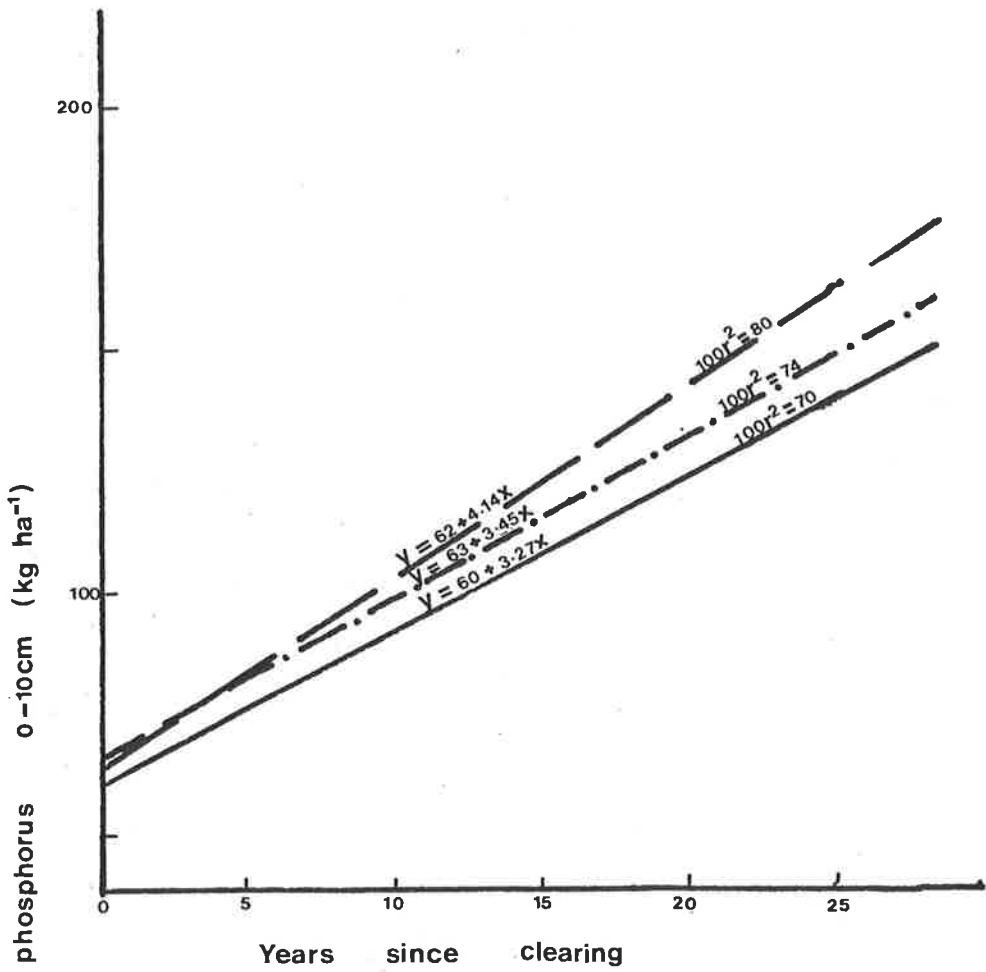
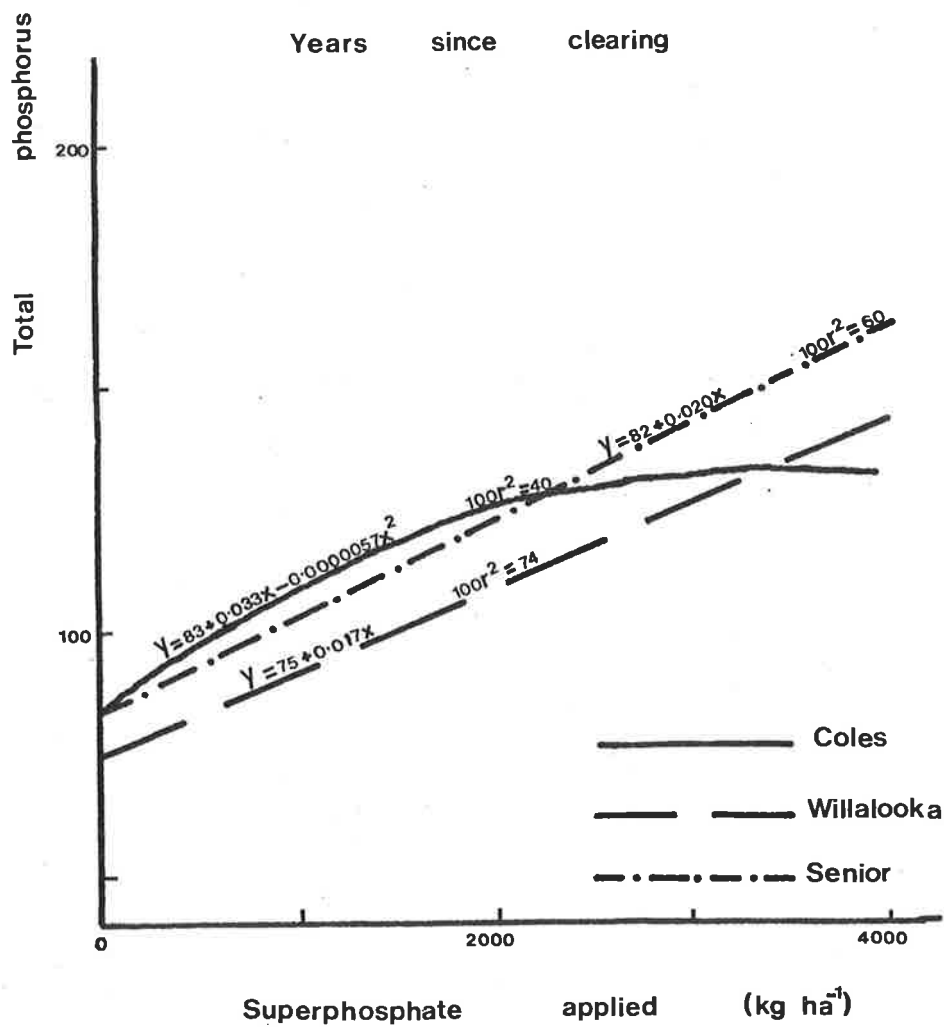
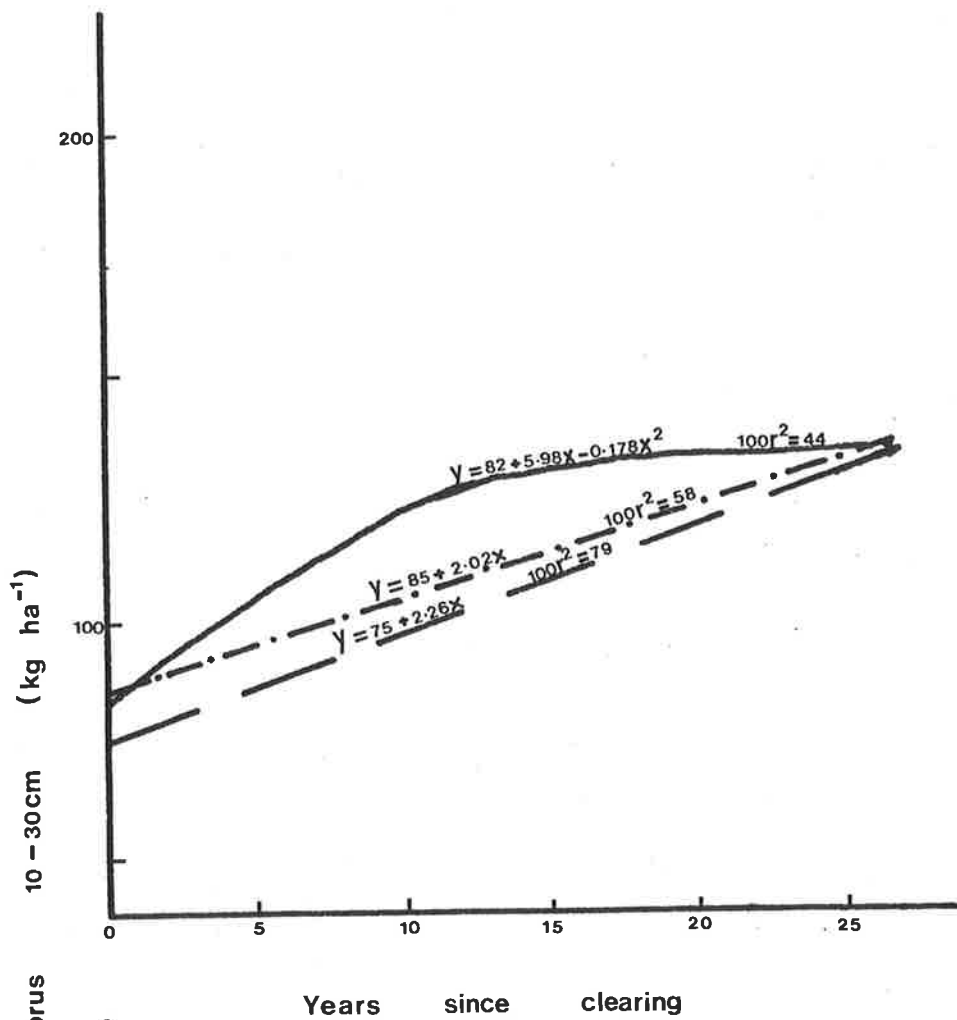


FIGURE 9

Accumulation of total phosphorus (kg ha^{-1}) in the
10-30 cm soil layer as related to years since clearing and
superphosphate applied (kg ha^{-1}), Hundreds of Coles,
Willalooka and Senior.



retention of phosphorus below the top layer. Similarly, Alston and Chin (1974) state that for the Mt. Compass soil, phosphorus leached out of the top 10 cm of soil is likely to be found in the sandy clay alluvial horizon. This conclusion is queried in the light of this work, since no significant increases of total phosphorus occurred in the 0 -7.5 cm clay layer for any of the three Hundreds. Therefore phosphorus not found in the sand horizon (0-clay layer) was presumed lost, due to either lateral movement to low swampy areas or drains or less likely movement through the clay layer to deeper horizons.

Therefore to draw up a balance sheet for phosphorus, values of total phosphorus in the surface to the clay layer were computed and these plotted against superphosphate applied. The results for the three regions are shown in Figure 10. Linear lines were fitted to the Senior and Willalooka data, while a quadratic relationship was found for the Coles data. To determine the amount of phosphorus applied still remaining in the soil, values were read off the curve and are shown in Table 18.

TABLE 18

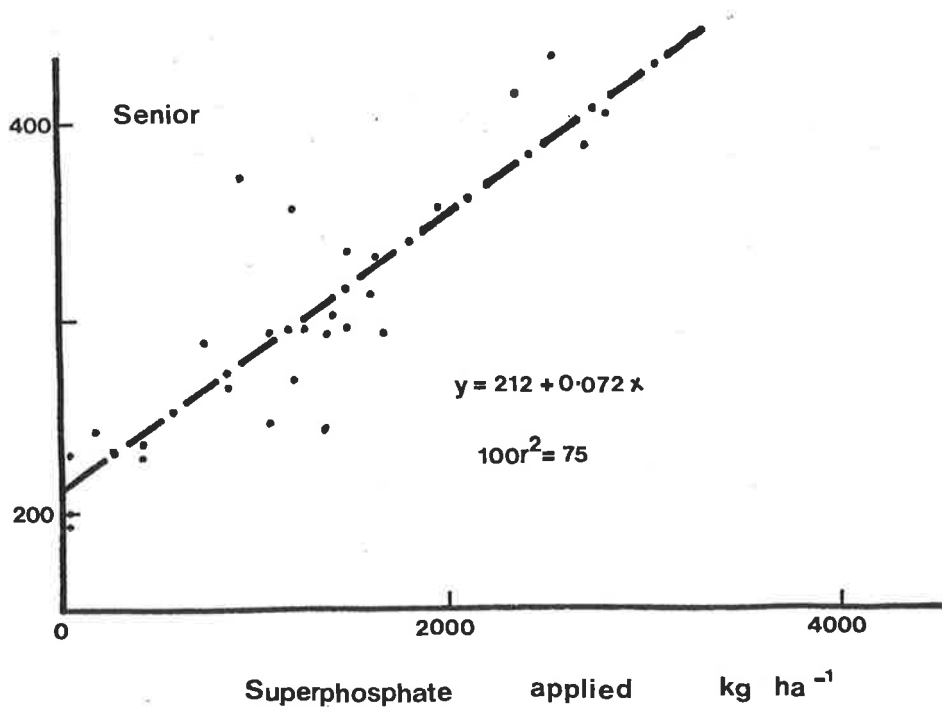
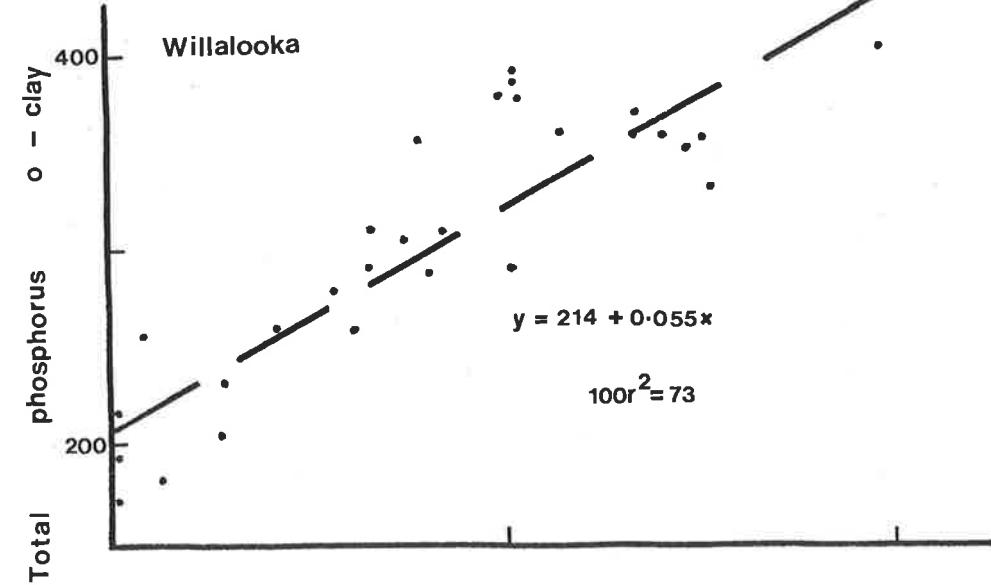
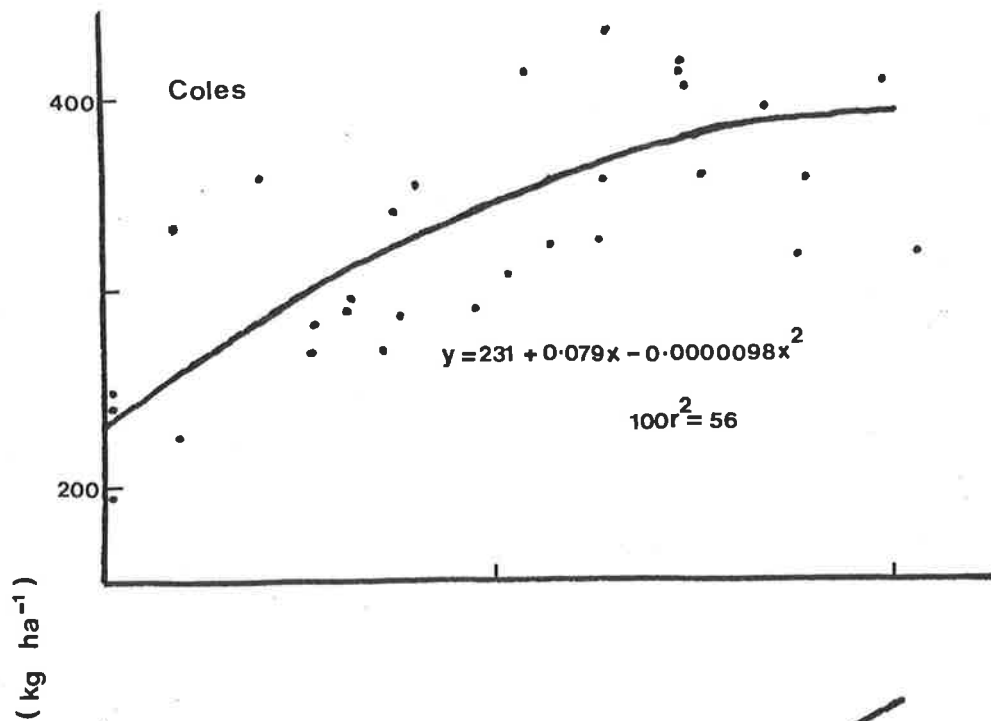
Increase in total phosphorus (kg ha^{-1}) as a result of different application rates (sand layer).

Hundred	Amount of phosphorus applied		
	180 kg P ha^{-1} (2000 kg super-phosphate ha^{-1})	270 kg P ha^{-1} (3000 kg super-phosphate ha^{-1})	360 kg P ha^{-1} (4000 kg super-phosphate ha^{-1})
Coles	118 (66)	148 (55)	158 (44)
Willalooka	110 (61)	165 (61)	220 (61)
Senior	144 (80)	216 (80)	288 (80)

N.B. Figures in brackets are percent recovery in the soil of phosphorus added.

FIGURE 10

Relationship between total phosphorus accumulation
(kg ha^{-1}) in the sand layer and superphosphate applied
(kg ha^{-1}), Hundreds of Coles, Willalooka and Senior.



Results presented in Table 18 further illustrate the low recovery of applied phosphorus in the Hundred of Coles. Although this area receives the highest average annual rainfall, it is thought that certain soil factors are more important than rainfall in controlling phosphorus retention. One of these soil properties is 'active' iron and values for the virgin sites were 15, 20 and 26 mg 100 g⁻¹ for Coles, Willalooka and Senior respectively. From these figures the highest retention of applied phosphorus would be expected in the Senior area and the lowest in Coles. Data presented in Table 18 confirm this. Further results relating to phosphorus leaching and factors controlling the rate of this loss are presented in Appendix 3. The relationships found in this study and in Appendix 3 agree with the findings of Ozanne et al., (1961) and Ballard and Fiskell (1974 a).

(b) Organic phosphorus

Accretion of organic phosphorus was measured in the 0-10 cm and 10-30 cm layers and the relationships for the three areas are: -

<u>Coles</u> (0-10 cm)	Organic P (ppm) = 15+3.00x-0.054x ^{2***}	(100r ² =71)
(10-30 cm)	Organic P (ppm) = 7.6+1.21x-0.034x ^{2***}	(100r ² =61)
<u>Willalooka</u>		
(0-10 cm)	Organic P (ppm) = 6.0+3.62x-0.068x ^{2***}	(100r ² =88)
(10-30 cm)	Organic P (ppm) = 2.8+0.72x-0.0049x ^{2***}	(100r ² =82)
<u>Senior</u> (0-10 cm)	Organic P (ppm) = 6.0+2.39x--0.050x ^{2***}	(100r ² =91)
(10-30 cm)	Organic P (ppm) = 2.4+0.31x ^{***}	(100r ² =66)

(where x = years since clearing)

Whereas total phosphorus accumulation tended to be linear with time, accretion of organic phosphorus declined with time. This was the case in the 0-10 cm layer for all regions, and the 10-30 cm layers for Coles and Willalooka. The relationships were very similar if superphosphate applied was used as the independent variable. Provided superphosphate was applied at rates necessary to produce optimum growth, organic

phosphorus accumulation will not be enhanced by applying additional phosphorus (Williams, 1950 a and Russell, 1960 b), since organic phosphorus build up results primarily from the decay of residual plant material or decomposition of dung.

The relationships found for organic phosphorus accumulation expressed as kg ha^{-1} , against years since clearing were: -

<u>Coles</u>	(0-10 cm)	Organic P (kg ha^{-1}) = $23+2.1x^{***}$	($100r^2=69$)
	(10-30 cm)	Organic P (kg ha^{-1}) = $20+3.82x-0.107x^{2***}$	($100r^2=63$)
<u>Willalooka</u>			
	(0-10 cm)	Organic P (kg ha^{-1}) = $8.0+4.3x-0.086x^{2***}$	($100r^2=87$)
	(10-30 cm)	Organic P (kg ha^{-1}) = $8.6+1.28x^{***}$	($100r^2=77$)
<u>Senior</u>	(0-10 cm)	Organic P (kg ha^{-1}) = $8.1+2.88x-0.058x^{2***}$	($100r^2=90$)
	(10-30 cm)	Organic P (kg ha^{-1}) = $6.7+0.84x^{***}$	($100r^2=64$)

(where x = years since clearing)

The inclusion of the bulk density factor tended to alter the shape of some curves, e.g. 0-10 cm layer for Hundred of Coles.

Using the curves above, organic phosphorus levels were computed for different pasture ages. These were then used to calculate rates of accumulation (Table 19).

Accumulation of organic phosphorus for all areas was greater in the first 12.5 years compared to the next 12.5 years for the 0-30 cm layer. Overall the build up was greater in the most southern area, contrasting with the total phosphorus data. As mentioned, this would be the result of greater dry matter production in the Coles area, as well as higher stocking rates (Bromfield, 1961). Another interesting finding is the accumulation of organic phosphorus in the 10-30 cm layers. In at least two instances this is occurring at a slightly greater rate than in the surface. This was not so in the trial reported by Russell (1960 b) at Kybybolite. However, the Kybybolite soil contained much

TABLE 19

Organic phosphorus levels and rate of accumulation at different stages of development.

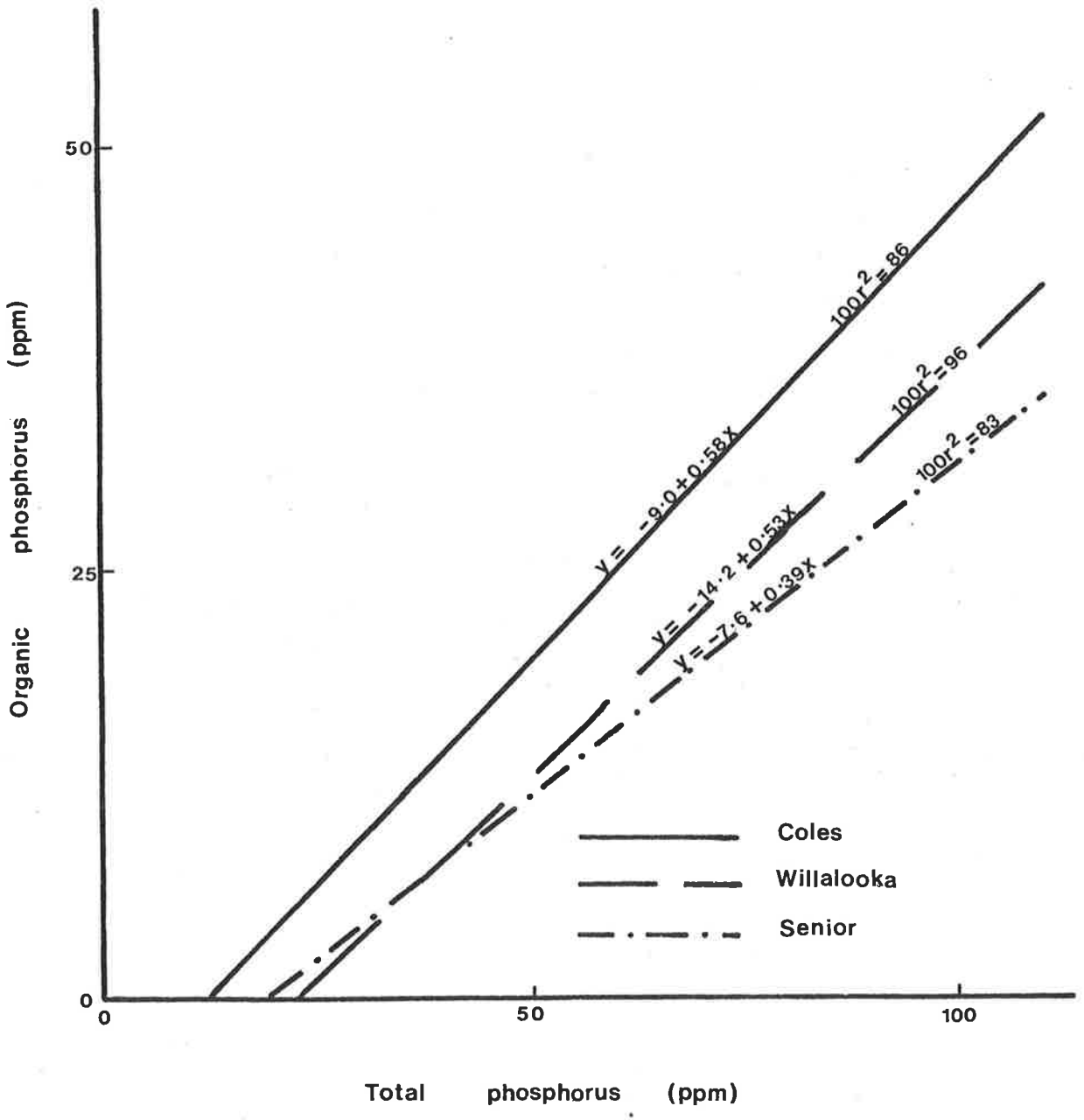
Hundred	Depth (cm)	Organic phosphorus kg ha ⁻¹ at different stages of development.			Rate of accumulation of organic phosphorus kg ha ⁻¹ yr ⁻¹ for two periods of development.	
		Virgin	12.5 years	25 years	Virgin - 12.5 years	12.5 years - 25 years
Coles	0-10	23	49	76	2.1	2.1
	10-30	20	51	62	2.5	0.9
					<u>4.6</u>	<u>3.0</u>
Willalooka	0-10	8	49	62	3.3	1.0
	10-30	9	25	41	1.3	1.3
					<u>4.6</u>	<u>2.3</u>
Senior	0-10	8	35	45	2.2	0.8
	10-30	7	17	28	0.8	0.9
					<u>3.0</u>	<u>1.7</u>

higher iron and aluminium contents in the surface and its believed that these elements enhance organic build up (Williams and Steinbergs, 1958; John et al., 1965).

In an attempt to compare the proportions of organic to total phosphorus in soils from the three regions, organic phosphorus (ppm) was plotted against total phosphorus (ppm). Lines were fitted and the results are illustrated in Figure 11. Taking 100 ppm total phosphorus as an example, a soil in the Coles region would contain 49 ppm organic phosphorus. Similarly, a Willalooka soil would have 39 ppm and a Senior soil 32 ppm. Part of this higher organic phosphorus percent in the Coles region is due to the higher levels in the virgin state (Table 19). These levels

FIGURE 11

Relationship between organic phosphorus (ppm) and total phosphorus (ppm) in the 0-10 cm soil layer.



probably being due to a denser vegetation in the wetter area (Nye and Bertheux, 1957; Wells and Saunders, 1960; Fares et al., 1974). However, overall organic phosphorus accumulation is expected to be greater in this region for reasons already mentioned. This means that in the drier areas, e.g. Senior, much of the total phosphorus accumulation is as inorganic phosphorus. The effect of this can be seen in the levels of available phosphorus in the three regions.

(c) "Available" phosphorus

"Available" soil phosphorus is considered as a guide for predicting growth response of a pasture to applied phosphorus (Lewis and Clarke, 1975). For this reason available phosphorus was measured for the 0-10 cm layers in both spring and autumn. It would be expected that available phosphorus levels may fall during the spring owing to plant uptake (Lewis and Clarke, 1975; French et al., 1976).

The values recorded in the spring sampling are plotted against superphosphate applied in Figure 12. Generally, the correlations were improved when the independent variable used was superphosphate in place of years since clearing. This was most obvious in the regression equations for Senior: -

where x = years since clearing

$$\text{Available phosphorus (ppm)} = 9 + 0.396x \quad (100r^2=32)$$

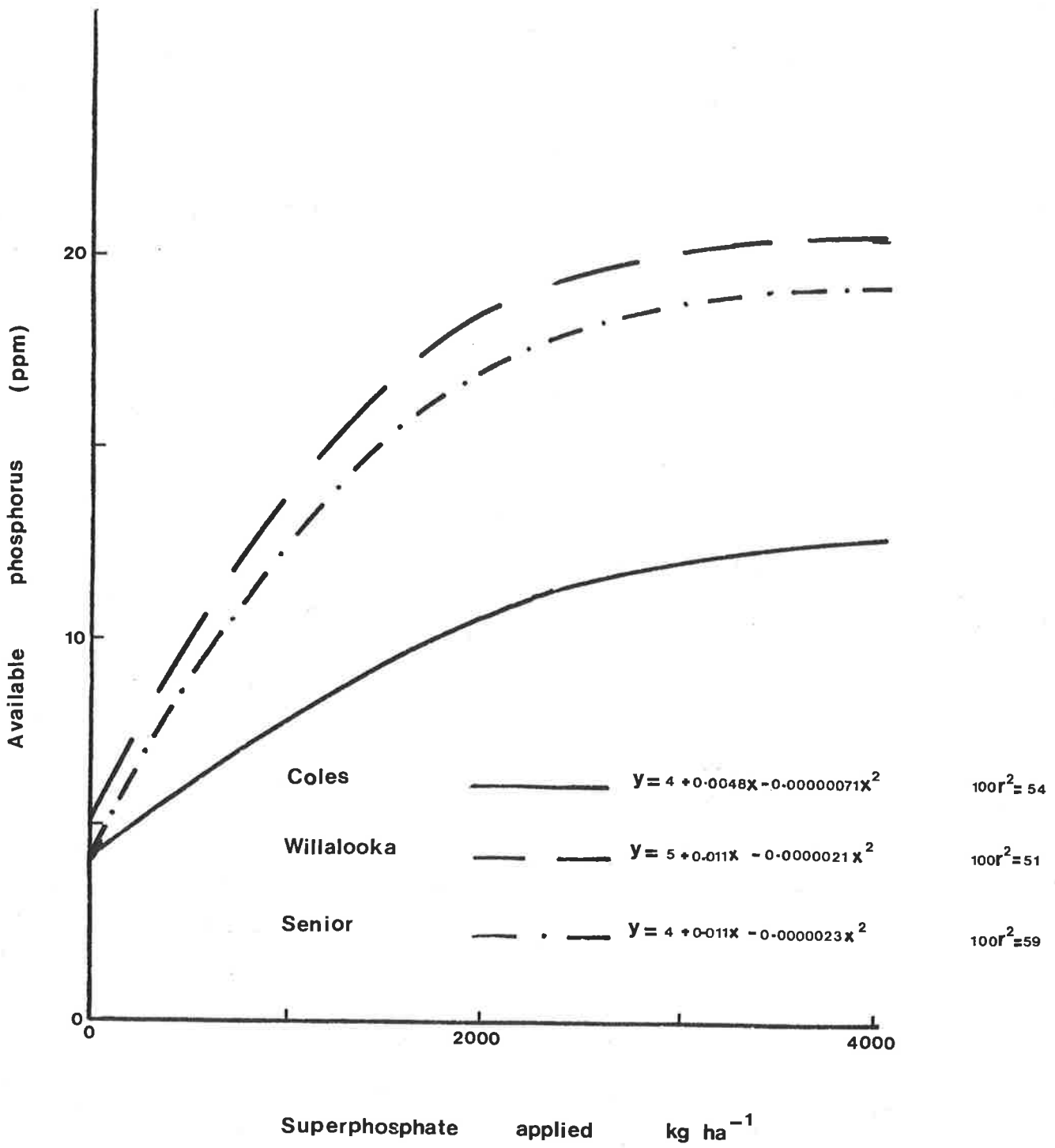
where x = superphosphate applied (kg ha^{-1})

$$\text{Available phosphorus (ppm)} = 4 + 0.011x - 0.0000023x^2 \quad (100r^2=59)$$

This would be expected as available phosphorus is very much a measure of recently applied phosphorus. The curves for the Willalooka and Senior areas are very similar, with a more rapid accumulation of available phosphorus for the first 2000 kg ha^{-1} of superphosphate than the second.

FIGURE 12

Relationship between available soil phosphorus (0-10cm)
measured in the spring and superphosphate applied (kg ha^{-1}),
Hundreds of Coles, Willalooka and Senior.



Lewis and Clarke (1975) consider values of around 20 ppm available phosphorus necessary before a sandy soil is said to have reached "maintenance phase". The data from the Coles area suggest that soils in that area are unlikely to reach maintenance level with respect to phosphorus. This finding is supported by data collected by Lewis et al., (pers. comm.) that showed an immediate decline in pasture growth if superphosphate was left off pasture that had previously received 3500 kg ha⁻¹ superphosphate.

Available phosphorus levels did not increase significantly during the autumn period. This is shown to some extent by the similarity between the two curves for the Coles area: -

Spring

$$\text{Available phosphorus (ppm)} = 4 + 0.98x - 0.028x^{2***} \quad (100r^2=55)$$

Autumn

$$\text{Available phosphorus (ppm)} = 3 + 0.94x - 0.031x^{2*} \quad (100r^2=33)$$

(where x = years since clearing)

This finding was not expected in the light of previous work in South Australia. Part of the answer may be due to lower than average superphosphate applications in 1975. Also variations in annual rainfall may effect the available phosphorus pool directly, by increasing leaching and indirectly by increasing plant growth and hence uptake. Therefore, in years of above average rainfall, variations in the available phosphorus pool would be expected to be greatest between seasons. Since the 1975 and 1976 seasons had below average annual rainfalls, the similarity between curves may thus be explained.

2. Sulphur accumulation

As with phosphorus, total sulphur accumulation occurred at a greater rate in the surface layers than at depth. The following

equations represent the accretion of total sulphur in the top 10 cm of soil for the three regions: -

Coles

$$\text{Total sulphur (ppm)} = 126 + 5.19x^{***} \quad (100r^2=72)$$

Willalooka

$$\text{Total sulphur (ppm)} = 85 + 5.60x^{***} \quad (100r^2=83)$$

Senior

$$\text{Total sulphur (ppm)} = 72 + 3.72x^{***} \quad (100r^2=91)$$

(where x = years since clearing)

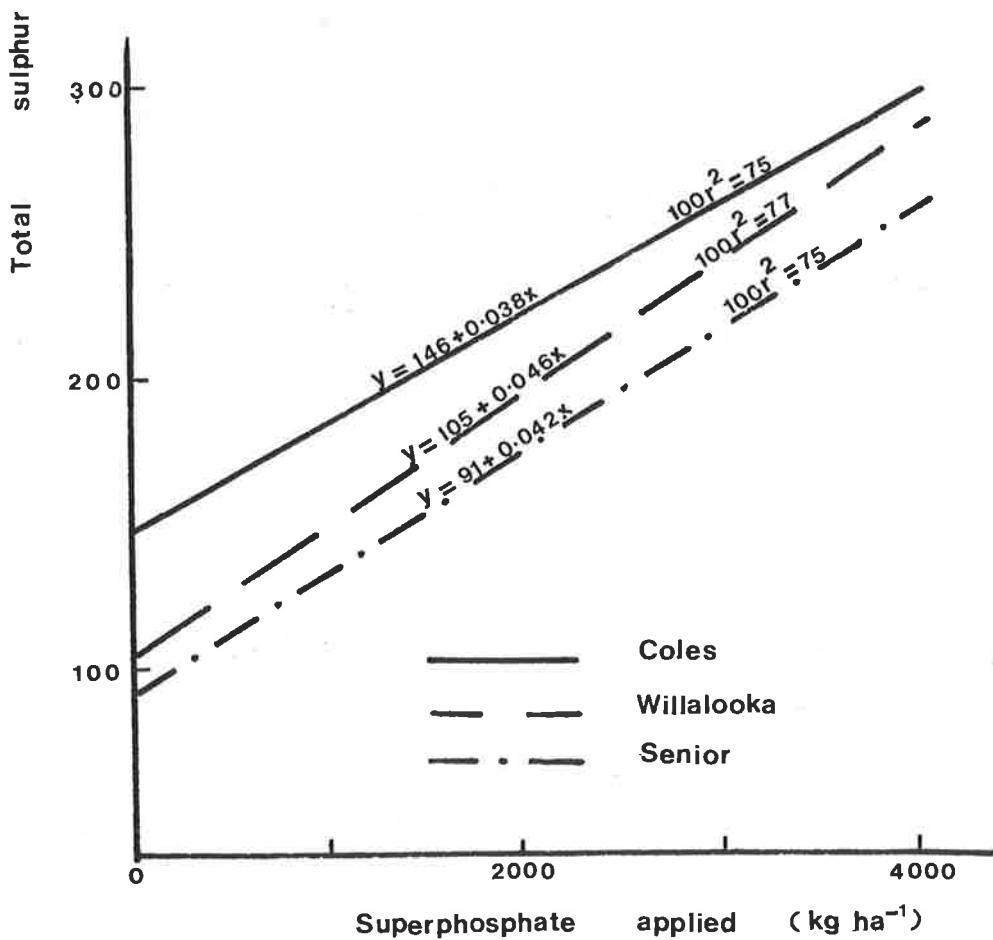
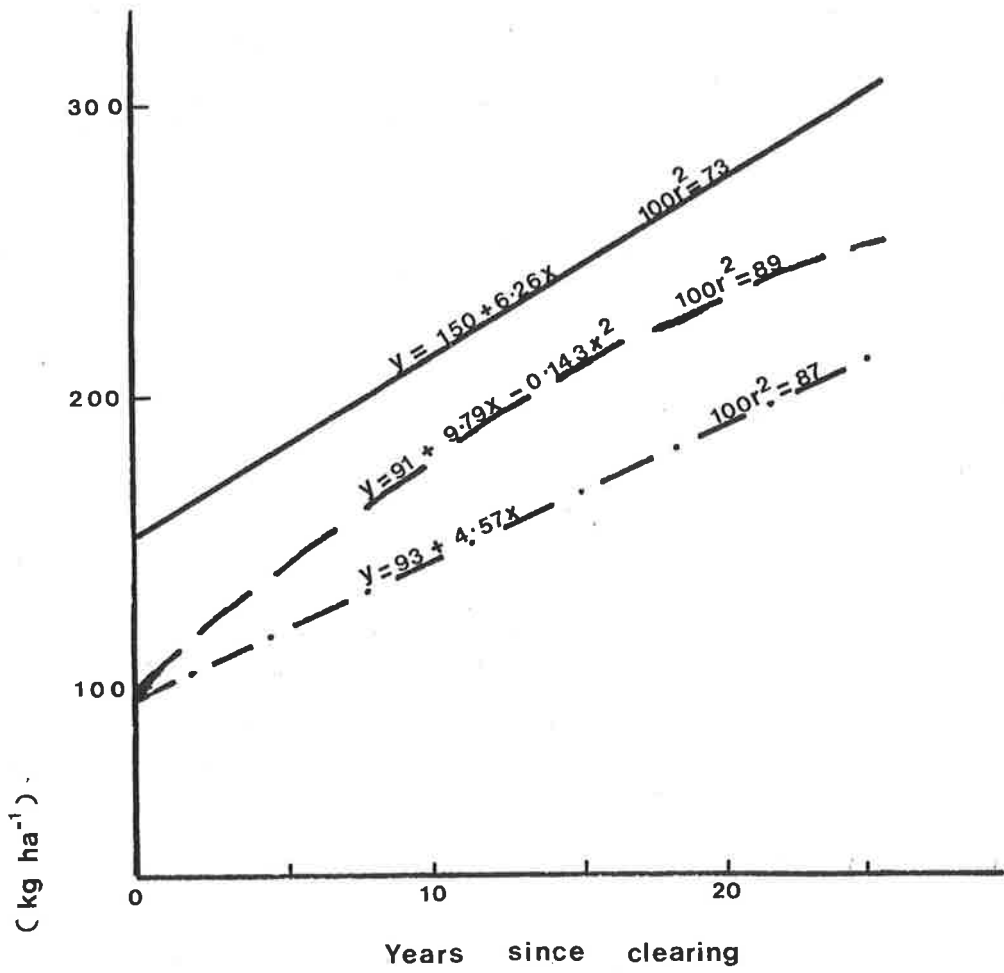
As inorganic sulphur levels in these soils, at any one time are very low (Nicolson, 1970; Clarke and Lewis, 1974) it can be assumed that the sulphur is present in organic forms. Therefore, as was shown with organic phosphorus, organic sulphur values in the virgin state were much higher in the wettest area, reflecting a more productive native vegetation.

Total sulphur accumulations expressed as kg ha^{-1} for the 0-10 cm layer are illustrated in figure 13. When plotted against years since clearing accumulation rates vary from $4.57 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for Senior to $6.26 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for Coles. These rates are very similar to those found by Barrow (1969) for the Coolup sand in Western Australia. However, they were much lower than those reported in New Zealand by Walker et al., (1959), i.e. $15.2 \text{ kg ha}^{-1} \text{ yr}^{-1}$.

The relationships between total sulphur accumulation in the 10-30 cm and 30 cm-clay layers with years since clearing and superphosphate applied, were generally not as significant as those for phosphorus. In fact, in only one area, i.e. Willalooka, was there found a significant relationship in the 30 cm to clay layer. Therefore, it can be concluded that total sulphur build up in the lower layers of the sandy soils was negligible.

FIGURE 13

Accumulation of total sulphur (kg ha^{-1}) in the
0-10cm soil layer as related to years since
clearing and superphosphate applied (kg ha^{-1})
Hundreds of Coles, Willalooka and Senior.



In an attempt to calculate the recovery of applied sulphur since development total sulphur (kg ha^{-1}) for the sand layer were calculated for each site. The relationships derived using superphosphate as the independent variable were:-

Coles

$$\text{Total sulphur (kg ha}^{-1}\text{)} = 712 + 0.046x^* \quad (100r^2 = 20)$$

Willalooka

$$\text{Total sulphur (kg ha}^{-1}\text{)} = 429 + 0.069x^{***} \quad (100r^2 = 48)$$

Senior

$$\text{Total sulphur (kg ha}^{-1}\text{)} = 369 + 0.063x^{***} \quad (100r^2 = 37)$$

Taking the sulphur content of superphosphate as 11 percent, recoveries in the soil were 42, 63 and 57 percent for Coles, Willalooka and Senior respectively. These figures therefore are very similar to those reported by Hingston (1959) and Watson (1969). With losses of around 50 percent of applied sulphur, the theory of Watson's (1959) that sulphur may be the limiting factor in organic matter accumulation in some Western Australian soils, may well hold for the sandy soils of the south east of South Australia.

3. Changes in other nutrients and properties

(a) Nitrogen

Considerable accumulation of total nitrogen has occurred with time for all three areas. Initially levels (0-10 cm) were very low,; 0.15, 0.04 and 0.09 percent for Coles, Willalooka and Senior respectively. This rate agrees with the findings of Taylor (1933) and Stephens and Donald (1958). The rates of build up (0-10 cm) with time (years) for the three regions are described by the following equations: -

Coles

$$\text{Total nitrogen (percent)} = 0.15 + 0.0046x^{***} \quad (100r^2 = 61)$$

Willalooka

$$\text{Total nitrogen (percent)} = 0.04 + 0.0043x^{***} \quad (100r^2 = 87)$$

Senior

$$\text{Total nitrogen (percent)} = 0.09 + 0.0031x^{***} \quad (100r^2 = 49)$$

The absolute rates of accretion for the three areas are shown in figure 14. Total nitrogen accumulated at rates of 55, 48 and 37 kg ha⁻¹yr⁻¹ for the Coles, Willalooka and Senior regions respectively. These rates are very similar to those reported by Watson (1963) of 47 kg ha⁻¹yr⁻¹ and Barrow (1969) of 38 kg ha⁻¹yr⁻¹ for sandy soils in Western Australia.

It could be argued that the different rates of change in nitrogen between the areas is due to differences in average annual superphosphate dressings (Table 11). Donald and Williams (1954) suggested that there was a linear relationship between soil nitrogen accumulation and superphosphate applied. However, Watson (1969) concluded that nitrogen accumulated at a greater rate if superphosphate was applied, but varying the rate from 42 to 375 kg ha⁻¹ did not alter the soil nitrogen levels. It is not possible to draw a conclusion from these data, except that for two regions, Willalooka and Senior, the significance of relationships for nitrogen accumulation were lowered by substituting years since clearing with superphosphate applied. While the relationships derived for the Coles region were unaltered, i.e.

Coles

$$\text{Total nitrogen (kg ha}^{-1}\text{)} = 1767 + 55.1x^{***} \quad (100r^2 = 69)$$

where x = years since clearing

$$\text{Total nitrogen (kg ha}^{-1}\text{)} = 1730 + 0.331x^{***} \quad (100r^2 = 70)$$

where x = superphosphate applied (kg ha⁻¹)

Willalooka

$$\text{Total nitrogen (kg ha}^{-1}\text{)} = 483 + 47.9x^{***} \quad (100r^2 = 89)$$

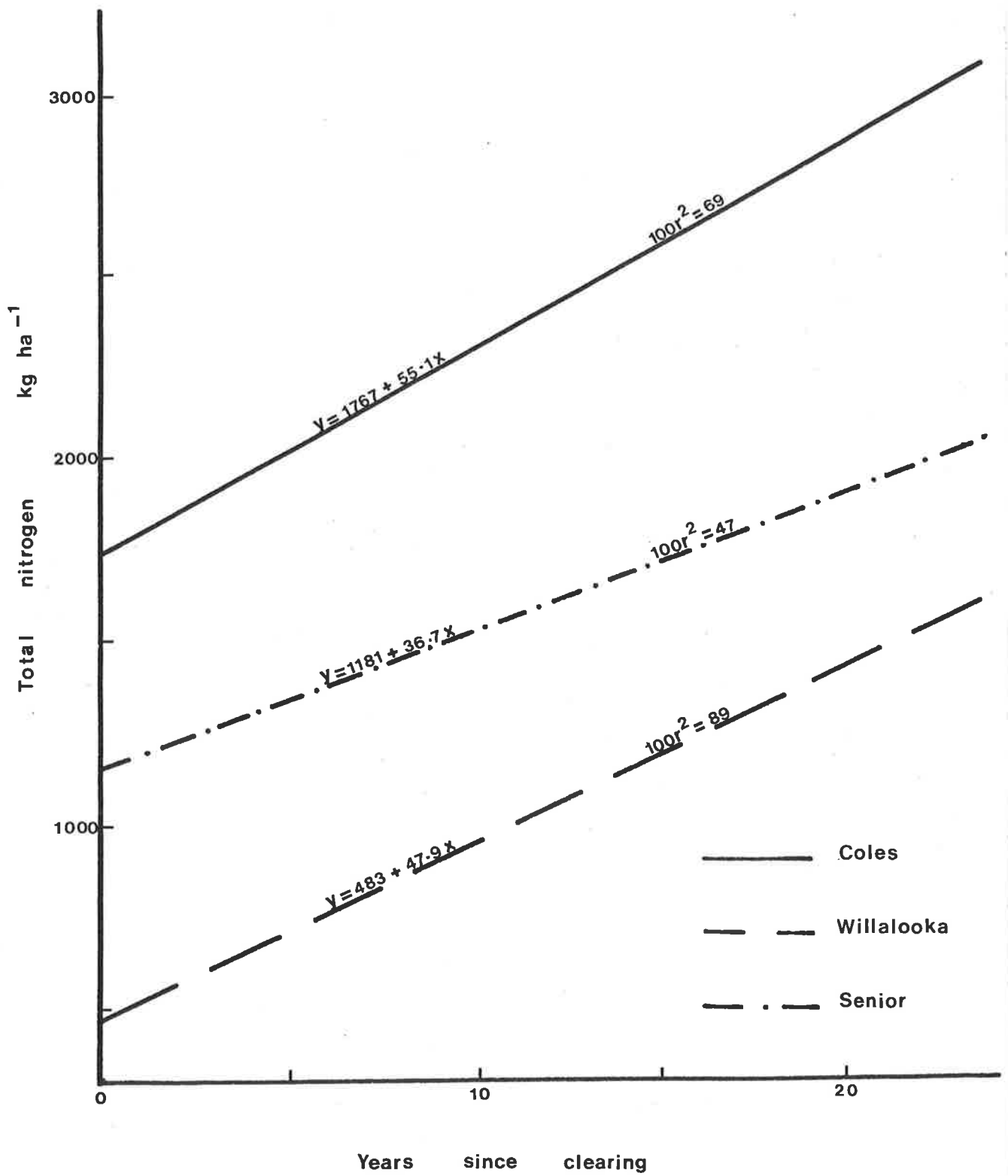
where x = years since clearing

$$\text{Total nitrogen (kg ha}^{-1}\text{)} = 481 + 0.361x^{***} \quad (100r^2 = 84)$$

where x = superphosphate applied (kg ha⁻¹)

FIGURE 14

Accumulation of total nitrogen (kg ha^{-1}) in the 0-10cm soil layer as related to years since clearing, Hundreds of Coles, Willalooka and Senior.



Senior

$$\text{Total nitrogen (kg ha}^{-1}\text{)} = 1181 + 36.7x^{***} \quad (100r^2=47)$$

where x = years since clearing

$$\text{Total nitrogen (kg ha}^{-1}\text{)} = 1201 + 0.309x^{**} \quad (100r^2=35)$$

where x = superphosphate applied (kg ha⁻¹)

The increased rate of nitrogen accumulation recorded in the Hundred of Coles may be partly the result of a denser and more vigorous legume component in those pastures (Table 14) compared with the other two Hundreds (Tables 15 and 16).

The data presented in Figure 14 show the linear build up of soil nitrogen with time. Richardson (1938) suggested that eventually this relationship will approach an asymptote. However, for these soils, this seems to be many years away.

This nitrogen accumulation has taken place in these areas in the absence of cropping. With reduced prices for livestock, there has been a move to cropping, e.g. cereals and oilseed crops. The value of this build up in soil nitrogen is realized once the soil is cropped. Nitrogen fertilizer costs around 40-45 cents kg⁻¹ and as such the annual soil nitrogen input from pastures is worth between \$15-\$20 ha⁻¹.

(b) Total calcium and potassium

Relationships found for total calcium accumulation with time were:

Coles

$$\text{Total calcium (ppm)} = 465 + 14.01x^{**} \quad (100r^2=25)$$

Willalooka

$$\text{Total calcium (ppm)} = 618 + 11.72x^{***} \quad (100r^2=37)$$

Senior

$$\text{Total calcium (ppm)} = 567 + 7.51x^{***} \quad (100r^2=39)$$

(where x = years since clearing)

Calcium accumulation with time has occurred at twice the rate for the Coles region as for the Senior region, i.e. $14.01 \text{ ppm yr}^{-1}$ compared with 7.51 ppm yr^{-1} . One reason for this greater accumulation in the Hundred of Coles would be the higher superphosphate application (Table 11). The significance of the regression equations is improved in all cases if superphosphate is used as the independent variable, suggesting that total calcium accretion has been largely affected by superphosphate applications: -

Coles

$$\text{Total calcium (ppm)} = 436 + 0.095x^{***} \quad (100r^2=32)$$

Willalooka

$$\text{Total calcium (ppm)} = 598 + 0.100x^{***} \quad (100r^2=45)$$

Senior

$$\text{Total calcium (ppm)} = 554 + 0.076x^{***} \quad (100r^2=41)$$

(where x = superphosphate applied (kg ha^{-1})).

The value of superphosphate in supplying calcium to sandy soils in the South East has been overlooked (Seeliger, persn. comm.) and in fact many calcium deficiencies have been alleviated as a result.

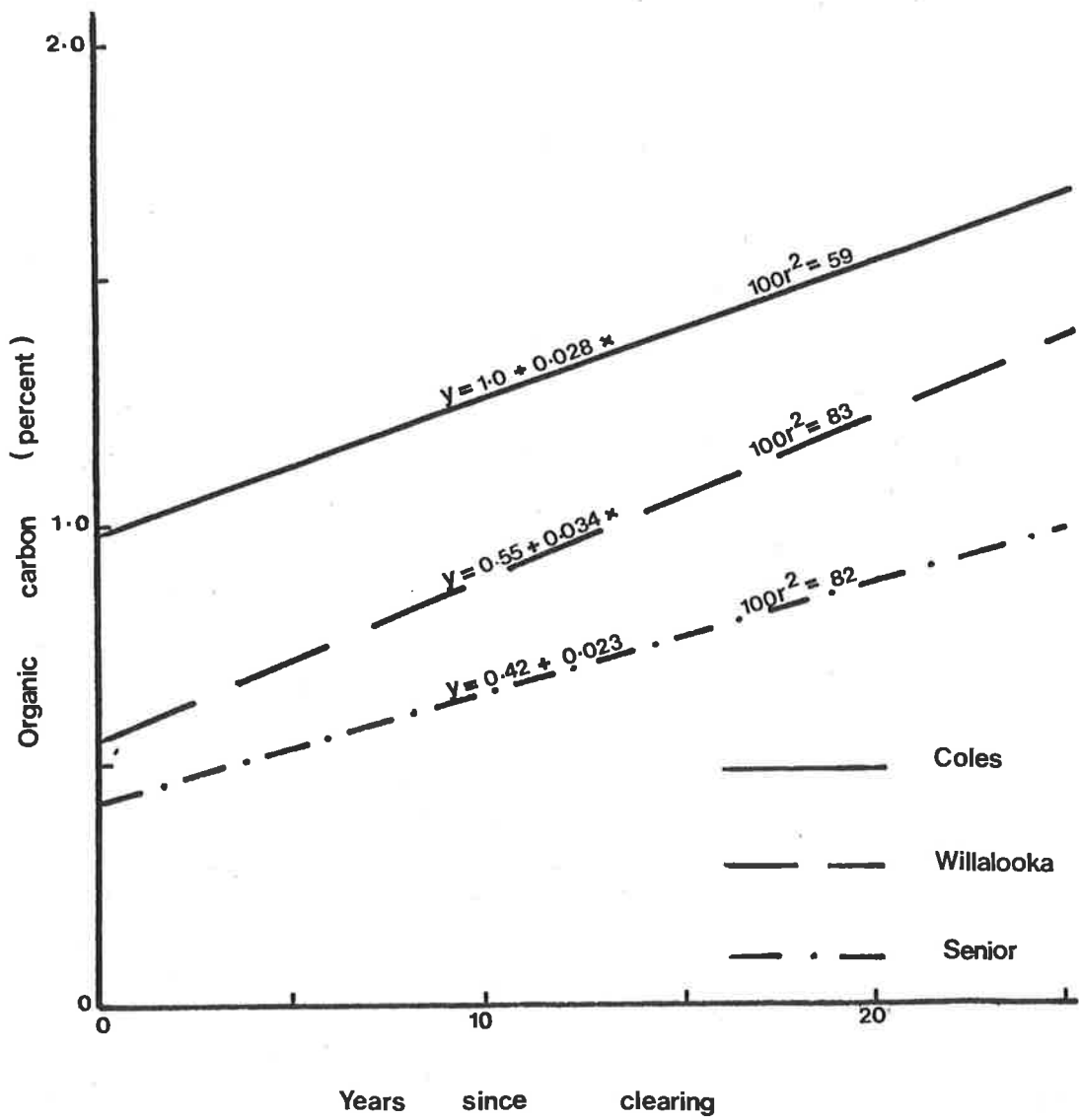
No significant relationships could be found for total soil potassium, suggesting that neither time since development or superphosphate applied affects the accumulation of this nutrient.

(c) Organic carbon

The accumulation of organic carbon in the top 10 cm soil for the areas is shown in Figure 15. There is little difference in rates of accretion, i.e. 0.028 , 0.034 and 0.023 percent yr^{-1} respectively for the Hundreds of Coles, Willalooka and Senior. These rates are very similar to those reported by Russell (1960 a) and Kohn et al., (1977). The twofold difference in organic carbon in the virgin state between Coles and Senior, reflects both the different vegetation and climate. Organic

FIGURE 15

Accumulation of organic carbon (percent) in the 0-10 cm soil layer as related to years since clearing; Hundreds of Coles, Willalooka and Senior.



carbon accumulation occurred in the 10-30 cm layer for Senior and Willalooka, but not for Coles. However, the actual amounts that accumulated were small, as is shown in the following equations: -

Willalooka

$$\text{Organic carbon (percent)} = 0.21 + 0.0046x^{***} \quad (100r^2=39)$$

Senior

$$\text{Organic carbon (percent)} = 0.16 + 0.0031x^{***} \quad (100r^2=44)$$

(where x = years since clearing)

(d) pH

The accumulation of organic matter, has resulted in a decline in pH in all three areas. The pH levels in the virgin state were 6.25, 6.80 and 7.00 for Coles, Willalooka and Senior respectively and the rates of decline after development were 0.017, 0.036 and 0.031 pH units yr⁻¹ in the top 10 cm for the same regions (Figure 16). The decline in pH values were also evident in the 10-30 cm layer (Figure 16). The data from the 10-30 cm layer suggests that an equilibrium is being reached with time in the Coles area.

The relationships were not as significant when superphosphate was included as the independent variable: -

Coles

$$(0-10 \text{ cm}) \text{ pH} = 6.25 - 0.000095x^{**} \quad (100r^2=25)$$

$$(10-30 \text{ cm}) \text{ pH} = 6.55 - 0.000076x^{**} \quad (100r^2=24)$$

Willalooka

$$(0-10 \text{ cm}) \text{ pH} = 6.15 - 0.000025x^{***} \quad (100r^2=63)$$

$$(10-30 \text{ cm}) \text{ pH} = 6.90 - 0.00018x^{***} \quad (100r^2=62)$$

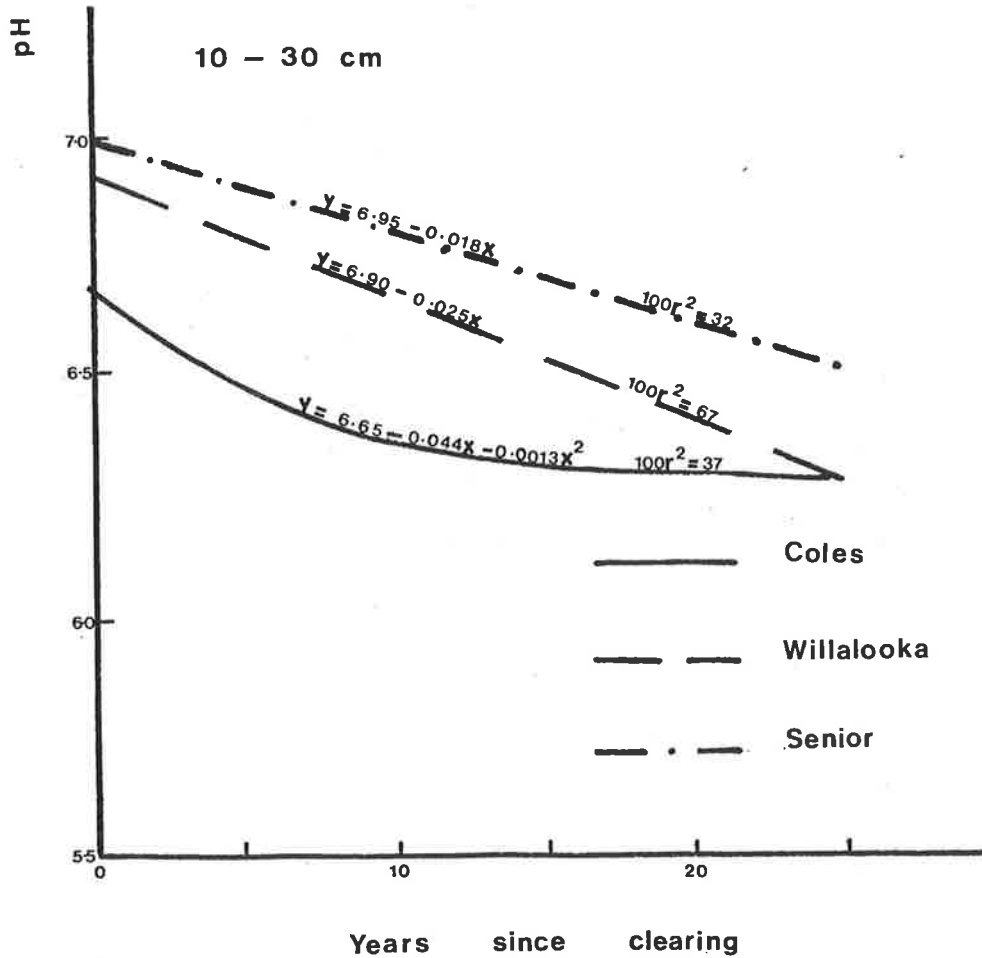
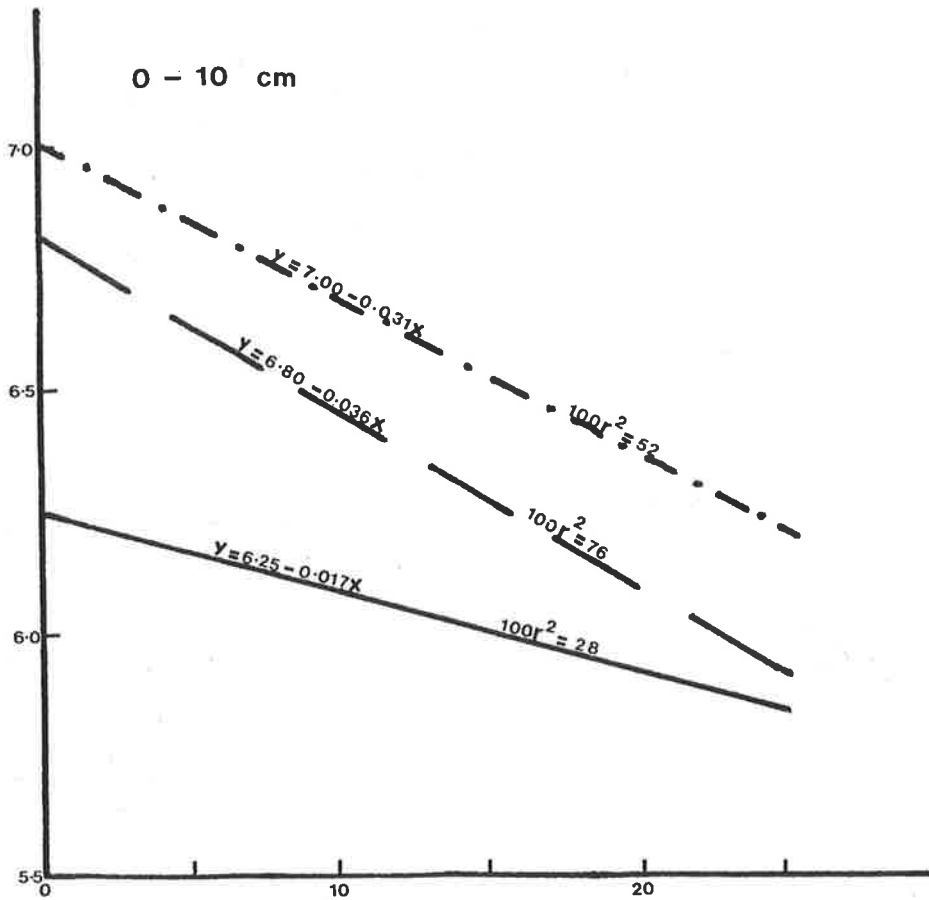
Senior

$$(0-10 \text{ cm}) \text{ pH} = 6.95 - 0.00026x^{***} \quad (100r^2=39)$$

$$(10-30 \text{ cm}) \text{ pH} = 6.95 - 0.00018x^{**} \quad (100r^2=32)$$

FIGURE 16

Relationships between soil pH and years since clearing in the 0-10 cm and 10-30 cm soil layers, Hundreds of Coles, Willalooka and Senior.



This suggests that the findings of Watson (1969) that pH decline is related more closely to age of pasture than applied superphosphate apply in this area. Therefore the increase in cation exchange capacity (see next section) that occurs with pasture development is thought to be the main reason why pH declines (Russell, 1960 a and Watson, 1969).

Pasture responses to applied lime in the area have been few (Seeliger, pers. comm.). However, it is likely with time, the pH levels in these sandy soils will fall below 5.0 and thus responses to lime may occur.

(e) Exchangeable cations and cation exchange capacity

Exchangeable calcium, magnesium and potassium levels were measured in the top 10 cm and 10-30 cm layers and the relationships relating these cations to age of pasture and superphosphate applied are shown in Table 20. No significant regressions were found for data from the 10-30 cm layer, suggesting that accumulation of exchangeable cations in these soils was confined to the top layer.

The increase in exchangeable calcium was greatest in Coles and lowest in Senior. This is attributed to the Coles region receiving higher superphosphate dressings and hence higher calcium inputs. Russell (1961) found similar results for soils in the Kybybolite trial, although plots receiving lime showed very much higher exchangeable calcium increases.

The increase in exchangeable magnesium as a result of the age of the pasture and fertilizer application is difficult to explain since the soils did not receive any magnesium. Although Russell (1961) found no effect of treatment on the exchangeable magnesium level in the 0-5 cm layer, there were increases in the 5-10 cm layer. Similarly, he gave no explanation as to why this should be so.

TABLE 20

Regression equations relating exchangeable calcium, magnesium and potassium to age of pasture and superphosphate applied.

Hundred	Exchangeable cation m.e. 100 g ⁻¹	x = age of pasture	100r ²	x = superphosphate applied (kg ha ⁻¹)	100r ²
Coles	calcium	y = 2.8+0.067x**	21	y = 2.6+0.00044x**	26
	magnesium	y = 0.44+0.0098x**	24	y = 0.42+0.000063x**	29
	potassium	n.s.		n.s.	
Willalooka	calcium	y = 2.05+0.055x***	37	y = 1.91+0.00050x***	50
	magnesium	y = 0.35+0.013x***	51	y = 0.36+0.000093x***	41
	potassium	y = 0.16+0.0063x*	22	y = 0.14+0.000058x**	32
Senior	calcium	y = 1.9+0.036x**	35	y = 1.9+0.00036x***	37
	magnesium	y = 0.31+0.0065x***	42	y = 0.30+0.000060x***	37
	potassium	y = 0.28+0.019x-0.0065x ² ***	45	y = 0.02+0.00016x-0.000000045x ² **	43

The relationship between exchangeable potassium and age of pasture increased in significance from Coles to Senior (Table 20). This may be explained firstly by the deeper rooted legumes being able to retrieve potassium from depth and secondly the lower rainfall in the Senior region reducing leaching. No records of potassium fertilizer applications were obtained, but in general they are very low in these areas. Therefore, as with exchangeable magnesium, the increases in exchangeable potassium in the top 10 cm must have come from within the soil profile.

Cation exchange capacity (0-10 cm) increased with pasture development, i.e.

Coles

$$\text{c.e.c. (m.e. } 100 \text{ g}^{-1}\text{)} = 3.3 + 0.055x^* \quad (100r^2 = 16)$$

Willalooka

$$\text{c.e.c. (m.e. } 100 \text{ g}^{-1}\text{)} = 3.1 + 0.069x^{***} \quad (100r^2 = 55)$$

Senior

$$\text{c.e.c. (m.e. } 100 \text{ g}^{-1}\text{)} = 2.0 + 0.049x^{***} \quad (100r^2 = 47)$$

(where x = years since clearing)

Both the greatest rate of increase $0.069 \text{ m.e. } 100 \text{ g}^{-1} \text{ yr}^{-1}$) and the most significant relationship was found for the Willalooka area.

Similar relationships were found when cation exchange capacity (0-10 cm) was related to superphosphate applied, i.e.

Coles

$$\text{c.e.c. (m.e. } 100 \text{ g}^{-1}\text{)} = 3.1 + 0.00037x^* \quad (100r^2 = 20)$$

Willalooka

$$\text{c.e.c. (m.e. } 100 \text{ g}^{-1}\text{)} = 3.07 + 0.0052x^{***} \quad (100r^2 = 51)$$

Senior

$$\text{c.e.c. (m.e. } 100 \text{ g}^{-1}\text{)} = 2.0 + 0.00041x \quad (100r^2 = 34)$$

(where x = superphosphate applied (kg ha^{-1})).

(f) C:N:P:S ratios

The ratios of C:N, C:P, C:S, N:P, N:S and S:P were calculated for each Hundred and relationships expressing the changes of these ratios with time and superphosphate applied are shown in Table 21. The results expressed are as ratios of the mean percentages of elements in 0-10 cm layer. Both carbon and phosphorus were organic values, while nitrogen and sulphur were total values. Since inorganic nitrogen and sulphur levels in these soils are low (Nicolson, 1970 and Lewis pers. comm.) the use of total values in the ratios would result in negligible change. From the equations presented in Table 21 C:N:P:S ratios for undeveloped pasture and pasture developed for 25 years were derived for the three Hundreds (Table 22).

TABLE 22

Changes in the ratios of C:N:P:S as a result of pasture development.

Hundred	Stage of development	Ratios of the constituents of the organic matter			
		C	N	P	S
Coles	Virgin	64	10	0.08	0.85
	25 yr pasture	63	10	0.20	0.92
Willalooka	Virgin	151	10	0.14	2.17
	25 yr pasture	97	10	0.40	1.64
Senior	Virgin	49	10	0.07	0.86
	25 yr pasture	60	10	0.23	0.99

The C:N ratios presented in Table 22 were not affected by pasture development in the Coles region, lowered in the Willalooka area and increased in the Hundred of Senior. The lowering of C:N ratio with time, as seen in data from the Willalooka area, has been observed by

TABLE 21

Regression equations relating various C:N:P:S ratios to years since clearing
and superphosphate applied.

Hundred	Ratio	x = years since clearing	100r ²	sig.	x = superphosphate applied (tonnes ha ⁻¹)	100r ²	sig.
COLES	C:N	n.s.			n.s.		
	C:P	y = 317+478e-0.36x	65	***	y = 322+485e-2.22x	63	***
	C:S	y = 78-0.478x	19	*	y = 78-3.6x	25	**
	N:P	y = 49+82.9e-0.44x	67	***	y = 49+82.1e-2.73x	67	***
	N:S	n.s.			n.s.		
	S:P	y = 4.6+6.05e-0.52x	66	***	y = 4.6+6.00e-3.35x	66	***
WILLALOOKA	C:N	y = 9.7+5.45e-0.17x	66	***	y = 9.6+5.80e-1.10x	69	***
	C:P	y = 259+765e-1.01x	94	***	y = 256+785e-5.71x	96	***
	C:S	n.s.			n.s.		
	N:P	y = 25+45.6e-1.93x	89	***	y = 25+45.7e-6.91x	89	***
	N:S	y = 6.4-2.04e-0.15x	58	***	y = 6.7-2.35e-0.81x	66	***
	S:P	y = 4.1+11.4e-0.93x	95	***	y = 4.0+11.6e-5.46x	97	***
SENIOR	C:N	y = 4.9+0.046x	21	*	y = 5.0+0.566x	24	**
	C:P	y = 254+438e-0.31x	85	***	y = 225+478e-1.60x	81	***
	C:S	n.s.			n.s.		
	N:P	y = 44 + 95.1e-0.250x	76	***	y = 34+106.6e-1.26x	75	***
	N:S	n.s.			n.s.		
	S:P	y = 4.3+7.98e-0.342x	80	***	y = 3.9+8.43e-1.80x	79	***

many workers (Hingston, 1959; Russell, 1960 a; Jackman, 1964; Watson, 1963 and 1969 and Kohn et al., 1977). Williams and Donald (1957) observed little change in the C:N ratio in soils they examined, a result similar to that shown in the Hundred of Coles. The low initial carbon values (Figure 15) in the undeveloped country of Senior may be one reason for the increase with time of C:N ratio in that area.

The changes in the C:P ratios with time for the three areas were very similar (Figure 17). The greatest change occurred in the first few years of development and after ten years the C:P ratio was relatively constant, at a value of approximately 300:1. Values in the virgin state ranged from 692:1 for Senior to 1024:1 for Willalooka. A value greater than 1000:1 for a C:P ratio in soil organic matter (0-10 cm) has very seldom been shown. Russell (1960 a) reported a value of 740:1 for a virgin soil in the Kybybolite area. The highest value found by Hingston (1959) for three virgin sandy soils in Western Australia was 341:1. Similar relationships were found when superphosphate was used as the independent variable.

Similarly for all three areas, the S:P ratio declined rapidly after the soil was sown down to pasture (Figure 18). After 10 years of pasture the S:P ratio reached a constant of between 4.1 and 4.6. The relationships were very similar for superphosphate applied (Table 21).

Both the C:P and S:P ratios for all three areas reached a constant value after approximately 10 years of pasture development. This time interval is very similar to that proposed by Lewis and Clark (1975) as the time necessary for a pasture to reach maintenance phase with respect to phosphorus. Therefore, it is feasible that the measurement of either the C:P or S:P ratio would tell a farmer if a certain paddock has reached maintenance level.

For both the Willalooka and Senior areas the C:S ratio did not change with either age of pasture or fertilizer applied. Results from

FIGURE 17

Changes in the C:P ratio as related to years since clearing, Hundreds of Coles, Willalooka and Senior.

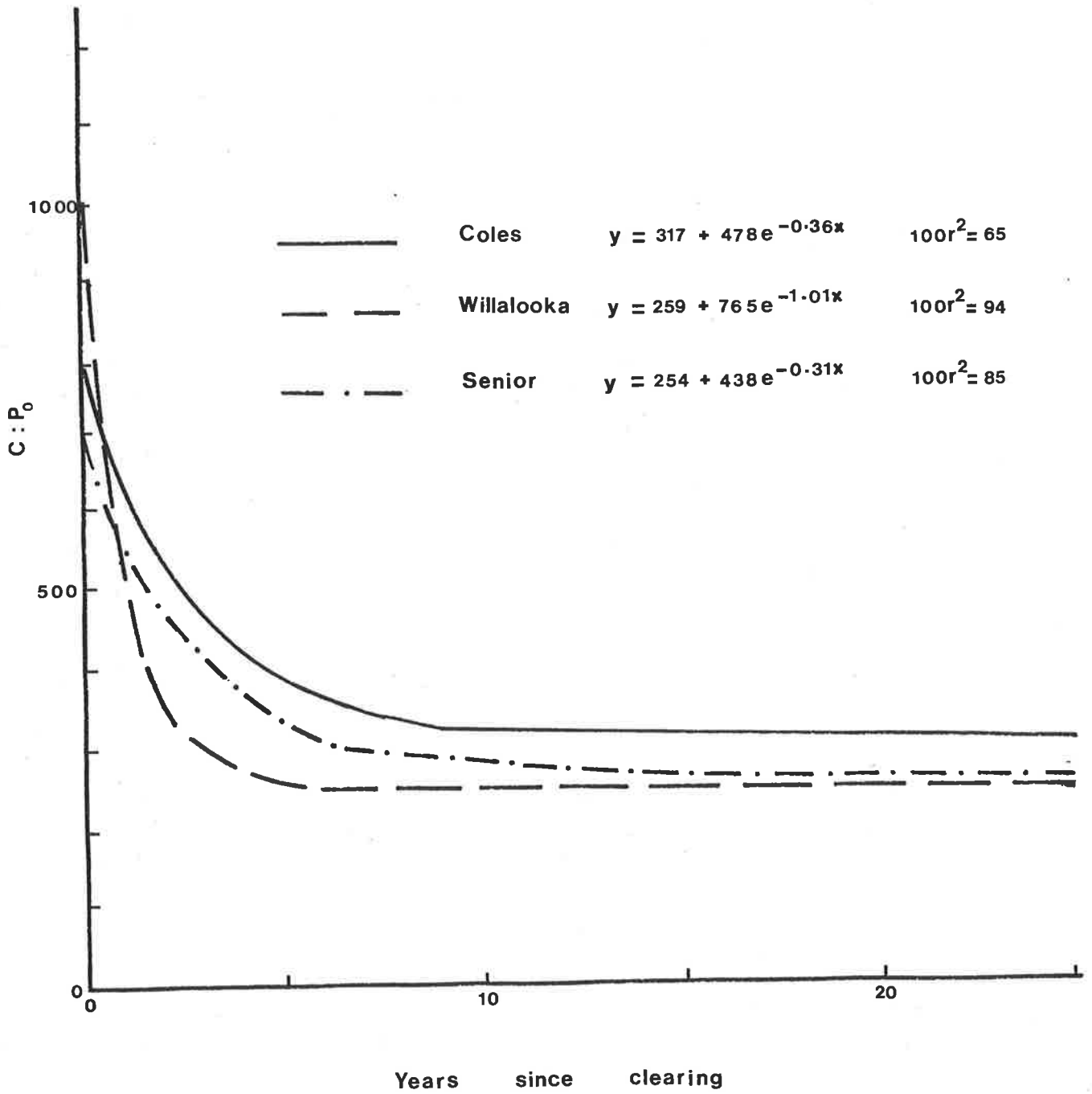
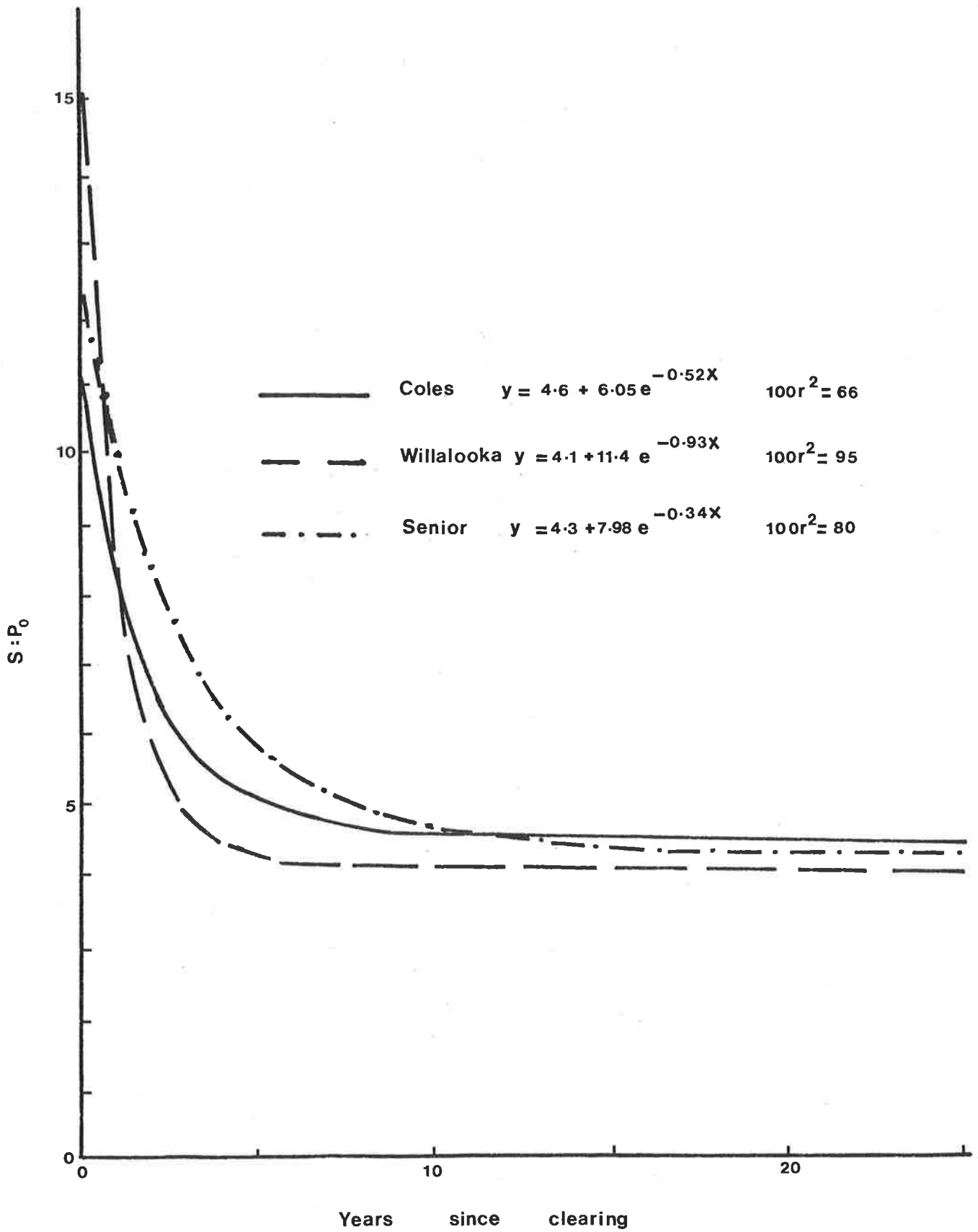


FIGURE 18

Changes in the S:P ratio as related to years since clearing, Hundreds of Coles, Willalooka and Senior.



the Coles region suggests that the C:S ratio declines with time, but the significance of the relationship is very low (Table 21). Similarly, results reported by Williams and Donald (1957) and Hingston (1959) indicate that the C:S ratio does not change with pasture development.

Similar to the changes in the C:P and S:P ratios, the N:P ratios also declined with pasture development (Table 21). After only two years of development in the Willalooka area the N:P ratio had fallen from a value of 70 in the undeveloped state to 25. Thereafter, the ratio remained reasonably constant. These results were similar to those reported by Russell (1960 a).

The N:S ratio was not affected by pasture development in the Coles or Senior areas, but did increase in the Willalooka area (Table 21). It is difficult to explain why the N:S ratio should change in only one area. However, Hingston's (1959) data (Table 10) shows a similar pattern, i.e. an increase in the Coolup sand but no change in the other two soils.

CALCULATION OF PHOSPHORUS AND SULPHUR
REQUIREMENTS FOR THE AREAS

Lewis and Clarke (1975) suggested that one way of tackling the problem of estimating phosphorus and, to a lesser extent sulphur requirements for grazed pastures was by way of a "balance sheet" approach. In this system the three major losses of phosphorus from the soil-plant-animal system are:

- (1) Net organic fixation
- (2) Leaching out of the root zone
- (3) Animal and plant removal.

This method has relevance once the soil has received a reasonable amount of superphosphate, i.e. it is said to have reached maintenance phase.

The criteria used to ascertain if soil has reached maintenance phase, has been by either using superphosphate applied since clearing i.e., sandy soils that have received 1.5 to 2.0 tonne ha⁻¹ or by available phosphate measurements, i.e., 15 to 20 ppm (Lewis and Clarke, 1975). As seen in the previous section, the use of C:P or S:P ratios may also be a possibility.

Paddocks that have not reached maintenance phase require quite heavy super dressing, usually 200 kg ha⁻¹ yr⁻¹ (Lewis and Clarke, 1975). The aim thereafter is to maintain production by replacing the phosphorus losses from a system, thus keeping phosphorus concentrations in the soil at a reasonably constant value.

In these calculations a number of assumptions were made. As the majority of pastures consist of annuals with shallow root systems (< 30 cm) it was assumed that phosphorus leached below 30 cm was lost to plant growth. It is realized that lucerne based pastures are a special case. Leaching losses (0-30 cm) of applied superphosphate for the three Hundreds were calculated from regression lines illustrated in Figures 8 and 9. Taking 3000 kg ha⁻¹ superphosphate as an average superphosphate dressing, then calculated leaching losses were 60, 46 and 40 percent respectively for Coles, Willalooka and Senior.

Organic phosphorus accumulation rates were taken from Table 19 (12.5 - 25 years data) while phosphorus removals in animal products were calculated using data from Russell (1960 b) and French et al., (1975). Allowances were also made for variations in stocking rates between Hundreds (Table 11).

Calculated maintenance phosphorus dressings: -

<u>Coles</u>	<u>kg ha⁻¹ yr⁻¹</u>
Phosphorus fixed as organic phosphorus	3.0
Phosphorus removed in animal products	1.5
	<u>4.5</u>
Phosphorus required, allowing for a 60 percent leaching loss	<u>11.3</u>
<u>Willalooka</u>	<u>kg ha⁻¹ yr⁻¹</u>
Phosphorus fixed as organic phosphorus	2.3
Phosphorus removed in animal products	1.2
	<u>3.5</u>
Phosphorus required, allowing for a 46 percent leaching loss	<u>6.5</u>
<u>Senior</u>	<u>kg ha⁻¹ yr⁻¹</u>
Phosphorus fixed as organic phosphorus	1.7
Phosphorus removed in animal products	1.0
	<u>2.7</u>
Phosphorus required, allowing for a 40 percent leaching loss	<u>4.5</u>

Therefore the annual maintenance superphosphate requirements for grazed annual pastures for Coles, Willalooka and Senior are 125, 70 and 50 kg ha⁻¹. If we assume that lucerne pastures can retrieve all leached phosphorus then the maintenance requirements for these pastures are 40 and 30 kg ha⁻¹ yr⁻¹ for Willalooka and Senior respectively.

In many instances the proposed maintenance superphosphate rates will not supply sufficient sulphur (Lewis and Clarke, 1975 and Lewis, unpublished data). Sulphur requirements by plants have been shown to be related to annual rainfall. In above average rainfall years sulphur requirements under grazing in the Coles area, have been shown to be as high as 20 kg ha⁻¹ sulphur. Therefore the use of sulphur fortified superphosphate has advantages in this situation. Similarly, these fertilizers may have advantages in the Willalooka and Senior areas. However, it must be stressed that the response or not to additional sulphur is dependent on the season.

AGRICULTURAL SIGNIFICANCE
OF THE RESULTS

As superphosphate is the most important fertilizer used in the south east of South Australia, the fate and value of this fertilizer is of great importance to the agricultural industry in the region. The exceedingly low recovery of applied superphosphate in the Hundreds, i.e. less than 50 percent in the sand layer, Hundred of Coles, raises the question of whether superphosphate is the most suitable fertilizer for the area. The problem is unlikely to be solved by applying small amounts more often as the relationships between leaching loss and applied phosphorus were linear for the Hundreds of Senior and Willalooka. A similar finding is reported in Appendix 3.

The use of lime may successfully reduce the movement of phosphorus down the profile (Clarke, 1974) and the use of less soluble fertilizers, such as rock phosphate (Alston and Chin, 1974 and Clarke, 1974) may be useful where leaching is severe. Calciphos is another less soluble fertilizer being tested in the area (Beckwith, pers. comm.) that may withstand leaching. For these fertilizers to be used as alternatives to superphosphate, a source of sulphur needs to be incorporated, since the sulphur requirements of these pastures are as great as the phosphorus requirements (Lewis and Clarke, 1975).

The value of the accumulation of organic matter with time and fertilizer applications, is only fully realized when these soils are cropped. Cropping has been of minor importance in past years, but with declines in the prices for meat and to a lesser extent wool, farmers are turning to cropping as an alternative farm practice. As such, these siliceous sandy soils are being cultivated and sown to a wide variety of cereal and oilseed crops. Indications are that the decline in organic matter under cropping is more rapid than accumulation and that excessive cultivations are speeding up this mineralization. Once mineralized the phosphorus, sulphur and nitrogen are subject to the leaching process already discussed. This thesis does not cover the

aspects of break down, but projects in the area are currently evaluating these processes. The place of minimum tillage in these soils is also being studied as one way of reducing the break down of organic matter.

Lime applications as a means of reducing phosphorus leaching have already been mentioned. However, lime will be needed in areas where the pH has fallen as a result of organic matter accretion. Of the three Hundreds examined, lime will be needed in the Coles region first. In fact, some sandy soils in the vicinity of this area have given values less than pH = 5.0. These soils are in many cases yielding poor crops due to low pH induced trace element deficiencies. Also pasture establishment has in many instances proven difficult (Marret, pers. comm.).

The very low organic phosphorus levels in the undeveloped state of these sandy soils results in very wide C:P, N:P and S:P ratios. The combination of pasture development and superphosphate applications results in a rapid narrowing of these ratios, to a stage where they reach an equilibrium. Results presented in this section would suggest that this equilibrium is reached after approximately 10 years. The implications of using this equilibrium in predicting whether or not a soil has reached maintenance phase with respect to phosphorus have already been discussed. One could hypothesise that if superphosphate was left off these pastures for a sufficient length of time, the ratios would tend to widen again. However, it is not possible to test this hypothesis with the data collected in this study, since all developed paddocks had received regular superphosphate dressings.

The use of the balance sheet approach as a means of determining superphosphate needs has been demonstrated in the previous section. The leaching values in this exercise have come from direct measurements. In Appendix 3 a simple phosphorus sorption test is suggested as a method for determining the leaching potential of a soil. Organic

phosphorus accumulations have been measured for three areas in this investigation and appear to be related to rainfall (Table 19). Therefore it may be possible to predict organic phosphorus accretion in these sandy soils from average rainfall figures. The final measurement is of animal removal. A value of 0.15 to 0.2 kg ha⁻¹ D.S.E.⁻¹ was used in the calculations. However, this figure will vary depending on whether wool or meat is removed or whether a paddock is cut for hay or cropped. The latter two practices will greatly enhance the phosphorus requirement (French et al., 1975).

Two sheep grazing trials have been conducted in these Hundreds, one in the Willalooka area and the other in the Coles region. Both with the specific aim of determining maintenance superphosphate rates. Results from the Willalooka trial indicated that an annual superphosphate dressing of 60 kg ha⁻¹ was necessary (Seeliger and Lewis, pers. comm.). This agrees very closely with the 70 kg ha⁻¹yr⁻¹ dressing proposed in this thesis. The other trial, in the Coles area, showed that an annual superphosphate dressing of slightly more than 100 kg ha⁻¹ was required. Once again supporting the findings presented in the previous section.

APPENDICES

APPENDIX 1

South Australia

DEPARTMENT OF AGRICULTURE & FISHERIES

Telephone: 64 7419

South East Regional Headquarters,

STD Code: 087

Box 618,

NARACOORTE. S.A. 5271.

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Dear,

For several years I have been conducting trials in the South-East to find out how much super is needed to maintain satisfactory pasture growth. My next aim in this project is to measure how much of the phosphorus applied in super is lost to plants by becoming tied up in organic matter in the soil. The best way to do this is to analyse soil taken from paddocks that have been cleared for various lengths of time. I wish to do this in the Hundred of

The most difficult problem is to find suitable sites to sample. Apart from finding paddocks of the right ages (Virgin scrub to about 25 years old), I need to pick areas with suitable soil which have had fairly normal stocking and super applications in the past. For this reason I am planning to conduct a simple survey of farms in the hundred. Could you please help me by taking part in this survey?

I enclose a questionnaire that is being sent to all farmers who have land in this hundred. This will supply all the information I need to help me find suitable sampling sites. I know that some questions will be difficult to answer exactly, particularly where land has changed hands. However, I hope you will help me as much as you can. All information supplied will be treated confidentially.

I plan to conduct the survey during the weeks beginning and will call then to collect the questionnaire and to help you fill it in, if necessary. I will phone you several days before calling. Meanwhile, if you wish to discuss the matter, please contact me at the Department's Regional Headquarters at Struan (phone: Struan 64 7419).

Yours sincerely,

D.C. Lewis

SOIL CONSERVATION BRANCH

FARM SURVEY, HD. OF

1. Location: Please list the section number(s) of your farm

2. Area: Total: acres

Cleared: acres

Cropped annually: acres

3. Soil: Please estimate as well as you can the area of each of the following kinds of soil that occur on your farm:

Acres or Percent

heavy or strong soil

shallow sands (less than 30 cm deep)
.....

medium sands (30-90 cm deep)

deep sands (more than 90 cm deep)
.....

4. Superphosphate: How much super have you usually applied each year per acre of cleared land?

..... lb acre⁻¹

How much have you applied annually during the last 4 years?

1972 lb acre⁻¹

1973 lb acre⁻¹

1974 lb acre⁻¹

1975 lb acre⁻¹

5. Livestock: Please state, in round figures the number of stock you now have: -

19....

Wethers

Dry ewes

Hoggets

Breeding ewes

Non breeding cattle
yearling or older

Breeding cows

APPENDIX 2

TABLE 23
Survey data, Hundred of Coles

Property	Total area (ha)	Percent cleared	Soil type (percent)				Superphosphate average annually (kg ha ⁻¹)	Stocking rate (D.S.E. ha ⁻¹)	Paddock age (years)							
			Heavy	Shallow sand	Medium sand	Deep sand			0	1-5	6-10	11-15	16-20	21-25	> 25	
1	715	92	-	-	95	5	187	8.0	*		1		7	1		
2	680	100	-	7	61	32	209	6.8					whole farm			
3	720	100	-	-	50	50	209	6.8		6	6	4				
4	440	48	-	82	9	9	208	16.0	*	4						
5	1331	72	-	83	9	8	168	10.3	*	2						
6	272	100	-	47	49	4	125	10.5					Whole farm			
7	2500	100	-	52	48	-	179	8.5					2	11		5
8	564	85	-	43	43	14	209	10.8	*		3	2	17			
9	5654	78	1	71	24	4	157	7.3	*	1	6	2	8	9		1
10	1630	98	49	26	25	-	168	8.3		3	2		15			9
11	431	96	71	29	-	-	190	8.0			5		22			
12	460	65	31	52	-	17	134	10.5	*				Whole farm			
13	361	89	-	30	59	11	157	12.5			2		20			
14	586	93	-	55	27	18	202	6.5					Whole farm			
15	2247	82	36	18	28	18	157	6.8	*	4	1	7	6	5		
16	495	81	3	45	31	21	190	8.5	*	2		13	6			
17	508	67	8	71	21	-	209	5.0	*				Whole farm			
18	714	64	-	65	10	25	-	7.3	*		3	4	2			
19	544	81	7	37	19	37	168	7.0	*		2	11				
20	376	85	21	-	51	28	209	7.5	*		1	21				
21	949	84	6	6	71	17	-	9.3	*	1	2	6				
22	451	82	-	-	80	20	182	6.8	*	4	3					
23	452	80	1	1	89	9	209	6.5	*	4	1	2				
24	512	86	-	-	80	20	157	6.8	*		1					
25	364	100	-	40	40	20	209	7.0		4	4					

TABLE 24
Survey data, Hundred of Willalooka

Property	Total area (ha)	Percent cleared	Soil type (percent)				Superphosphate average annually (kg ha ⁻¹)	Stocking rate (D.S.E. ha ⁻¹)	Paddock age (years)										
			Heavy	Shallow sand	Medium sand	Deep sand			0	1-5	6-10	11-15	16-20	21-25	> 25				
1	354	100		68	32		112												3
2	1120	79	2	61	23	14	134				2								18
3	511	98	1	77	20	2	157				3	4							14
4	508	95	8	39	47	6	112		*		3	2		6					12
5	447	94	11	54	28	7	-												
6	393	99	8	26	60	6	202												
7	379	84	38	62			-												
8	367	100	89	11			112					4							15
9	378	99	98	1	1		134							8					18
10	252	95	95	5			-												
11	775	98	15	70	15		90												Section 13
12	313	100		94		6	134												Section 13
13	368	98			90	10	-												Section 13
14	640	98	13	56	18	13	125							4					27 1
15	644	98	6	63	25	6	125					2		5					16
16	1492	99	27	11	30	32	112					8		23					2
17	739	95	7	62	29	2	101		*		1	1		4					10
18	804	75	20	70	10		125		*			2		4					5
19	1480	54	5	27	58	10	157		*	2	2	2		2					1
20	660	97		48	48	4	134												Whole farm
21	576	100	19	61	15	5	168												Whole farm
22	578	83	1	72	21	6	112		*	1									24
23	691	87	23	49	14	14	112		*					8					12
24	750	72	13	53	21	13	101					3		14					1
25	486	90		43	24	33	134		*		1			1					20
26	489	100	49		39	12	123												Whole farm
27	431	99	19	77		4	125					1		1					22

TABLE 24 (cont.)

Property	Total area (ha)	Percent cleared	Soil type (percent)				Superphosphate average annually (kg ha ⁻¹)	Stocking rate (D.S.E. ha ⁻¹)	Paddock age (years)						
			Heavy	Shallow sand	Medium sand	Deep sand			0	1-5	6-10	11-15	16-20	21-25	> 25
28	509	99	24	65		11	125	9.0		1	2	1	5	15	
29	496	98		48	52		134	9.3						Whole farm	
30	393	100			69	31	112	8.8						Whole farm	
31	497	100			100		125	8.5		1					
32	769	97	1		89	10	125	7.3			3	4		20	
33	440	100	19	72	9		125	6.3					8	6	3
34	200	85	16	20		68	-	6.3						7	
35	553	98		76	11	13	125	6.3			1	4	3	9	3
36	460	100	35	65			112	8.0					1	9	2
37	1452	90	12	2	75	11	67	6.8							
38	416	100	9	5	86		-	6.0							
39	240	42	32	68			209	5.0		1	1	3			
40	1135	81	2	65	33		125	4.8			3	4			
41	660	100	6	55	21	18	125	9.3							
42	600	73	25	59	7	9	104	9.0						20	
43	494	89	16	43	24	17	125	7.5						20	
44	755	42		38	50	12	209	4.8	*	1	4				
45	1322	97	16	28	44	12	157	7.8		7	4	5	32		
46	500	97	97		3		101	7.0						8	
47	1146	100			91	9	209	8.3		6	8			8	
48	520	94	10	45	45		251	14.8						24	
49	673	100			100		209	7.8							

TABLE 25
Survey data, Hundred of Senior

Property	Total area (ha)	Percent cleared	Soil type (percent)				Superphosphate average annually (kg ha ⁻¹)	Stocking rate (D.S.E. ha ⁻¹)	Paddock age (years)								
			Heavy	Shallow sand	Medium sand	Deep sand			0	1-5	6-10	11-15	16-20	21-25	> 25		
1	448	100	18	45	28	9	73	7.0									Whole farm
2	712	84	8	42	42	8	119	5.8									17
3	686	99	18	29	29	24	125	7.5					5				11
4	896	94	24	24	33	19	125	4.8									24
5	511	98	24	32	32	12	134	11.0			4						25
6	1704	86	10	50	25	15	124	4.5									
7	384	100		73	21	5	-	6.8									
8	1273	79	2	39	24	35	63	5.8	*								13
9	1032	97	34	8	13	45	63	3.8		1	1	9	16				10
10	406	98		10	45	45	125	4.3									
11	400	90		60	20	20	-	7.5									
12	1005	76	47	14	10	29	63	8.5		8	2			2			1
13	620	77	39	16	19	26	12	5.8	*		4	3					
14	308	95	10	69	15	6	67	8.5				4					8
15	478	100	50	8	16	26	112	5.3									15
16	3876	100	20	40	40		104	4.0				20	28				
17	11967	90	7	33	50	10	149	4.5		12	18	4	21				
18	2760	97	20	50	10	20	209	6.8	*	13	16						
19	800	80	21	29	36	14	104	4.3			4	2	5			3	
20	565	91	10	28	14	48	101	5.3			4					10	20
21	640	96	40	20	10	30	101	6.3			8		1			1	2
22	396	95		40	20	40	101	6.3		1							
23	431	85	19	34	47		-	3.3			6						
24	630	95	32		13	55	104	7.5				10					
25	828	96	25	28	25	22	125	4.8				3	7				10
26	400	100		33	33	34	101	4.3			7						

APPENDIX 3

The following paper has been submitted to Aust. J. Soil Res. Before accepting the paper the editor requires the authors to make minor alterations to the statistical analyses. These have yet to be completed. However, it was decided to include the paper since the results presented are relevant to the present study. Both table and figure numbers have not been altered. Also references have been included, so that the paper can be read as a separate item.

Factors Affecting the Leaching of Phosphorus
Applied as Superphosphate to Sandy Soils
in South Eastern South Australia

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Abstract

The recovery of phosphorus applied as superphosphate was measured in 31 multi-rate experiments on siliceous sands in the South-East of South Australia. The amount of phosphorus recovered in the top 30 cm of soil and in harvested pasture 5 months after application increased linearly with the amount applied at 16 sites and quadratically at 3, and there was no significant relation ($P < 0.10$) at 12 sites.

The proportion of phosphorus recovered when 40 kg ha^{-1} was applied (recovery P_{40}), read from the 19 fitted recovery curves, ranged from 10 to 100% and averaged 60%. Recovery P_{40} was closely correlated with P sorption values measured in the top 10cm of soil (quadratic $r = 0.82^{***}$), and with soil properties that affect sorption, namely 'active' iron ($r = 0.81^{***}$) and 'active' aluminium ($r = 0.69^{**}$). Rainfall during the experiments varied from 168 to 484 mm, but had no effect on recovery. Neither did the other soil properties measured, namely, pH, percent sand and organic carbon in the top soil, and depth to underlying clay.

Some agronomic implications of the leaching losses are discussed. It is considered that a simplified measure of P sorption is a useful indicator of leaching, and could assist in determining phosphorus recommendations in the region.

Introduction

There is ample evidence that phosphorus applied in water soluble form is sometimes leached from the surface layer of sandy soils. Leaching losses of up to 100% of the phosphorus applied over periods of 1-40 years have been reported from the top 10 to 30 cm of sandy soil (Hingston 1959; Russell 1960; Ozanne et al 1961; Alston and Chin 1974; Clarke 1974). As agriculture on these soils is based largely on the grazing of shallow rooted annual pastures, retention of phosphate within the top soil is desirable, and an understanding of the factors affecting retention is required.

Ballard and Fiskell (1974) showed by laboratory measurements that the amount of extracted aluminium and iron usefully characterized the leaching properties of sands with respect to phosphorus. In the field, Ozanne et al (1961) found that phosphorus leached from the top 10 cm was most closely related to loss on ignition, followed by native phosphorus concentration and extractable aluminium.

In the South-East of South Australia siliceous sands comprise approximately 60 percent of the agricultural land (Blackburn 1959, 1964). The aims of this investigation were to measure the extent of phosphorus leaching and the factors affecting its magnitude in siliceous sands in this region.

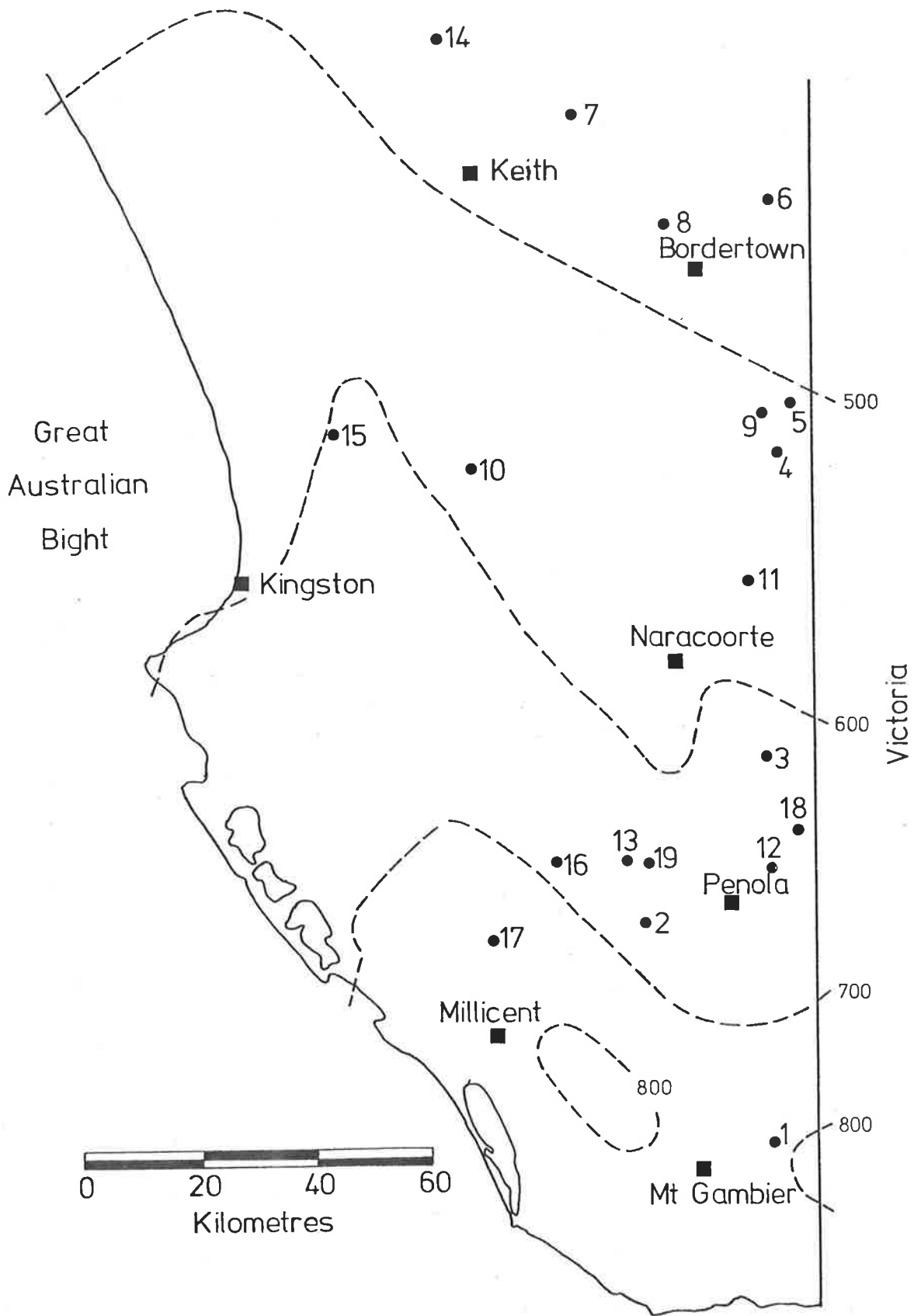
Materials and Methods

Field Experiments

From 1971 to 1973, 31 one-year trials were conducted. For reasons given below the results of only 19 were accepted, and their locations are shown in Fig. 1. The climate of the region is cool Mediterranean. The average annual rainfall is 500-800 mm, with over 80% falling during the months April to November.

Sites were selected on soils having 30-100 cm of sand overlying clay or sandy clay subsoil. The top soils were mostly weakly acid

Fig. 1. Location of experimental sites (numbered 1-19) and mean annual rainfall isohyets (mm) for the South - East of South Australia.



and contained low to moderate amounts of organic matter (Table 1).

The sites had been cleared of native vegetation and sown to pasture 5-15 years previously. The existing pasture was used in the trial if it was satisfactory; otherwise a new pasture of subterranean clover (Trifolium subterraneum L, cvs. Mt. Barker and Woogenellup - 40 kg ha⁻¹) and perennial ryegrass (Lolium perenne L. - 5 kg ha⁻¹) was sown and rolled after the site had been rotary hoed and harrowed.

Fifteen unreplicated rates of phosphorus, 0-80 kg ha⁻¹ P, were applied as single superphosphate at each site in May, after autumn rains had fallen. The size distribution of fertilizer particles was <0.8 mm, 4.1%; 0.8 - 1.1 mm, 16.5%; 1.1 - 1.9 mm, 54.3%; 1.9 - 4.8 mm, 24.3%. Plots measured 7 m x 1.5 m. Pasture was mown with a flail mower at 5 cm height in late winter (August) and again at 3 cm in spring (October).

Sample Collection and Analysis

The soil in each plot was sampled just before treatments were applied and again when the spring harvest was made 5 months later. The soil was sampled at 0-10 and 10-30 cm depths with a double-tube sampler of 3.1 cm internal diameter, ten cores being taken at random from each plot and bulked. These samples were analysed for phosphorus and used to measure changes in the amount of phosphorus present in the soil. Before analysis they were ground either to pass through a 0.5 mm sieve (1971 and 1972), or to a fine powder by milling for 1 min. in a Sieb-technik mill. The latter procedure reduced sub-sampling errors by ensuring thorough mixing of organic and inorganic soil components.

To characterize each site, soil samples (0-10 and 10-30 cm) were also collected from ten positions just outside the plots with a 5 cm 'Jarret' auger, and the depth to clay was measured. Rainfall was recorded daily at each site. At each harvest mown herbage was weighed and dried samples were collected for analysis.

Table 1. Description of some soil properties and the amount of rainfall recorded at trial sites

Site No. ^A	Great soil group	Northcote reference (1971)	Soil Properties ^B							Rainfall during leaching period ^C (mm)	
			Sand %	Organic C %	pH	Total P (ppm)	Active Fe (mg 100g ⁻¹)	Active Al (mg 100g ⁻¹)	P sorption at 1.0 ppm (ug g ⁻¹)		Depth to clay (cm)
1	Solodized solonetz	Db 4.21	88	1.35	5.5	177	101	53	19.0	62	484
2	Ground water podzol	Dy 5.62	92	1.80	6.3	109	46	25	9.6	40	414
3	Solodized solonetz	Dy 5.21	92	1.23	5.5	110	49	45	12.5	39	315
4	Solodized solonetz	Dy 5.31	92	1.31	5.9	75	12	15	-4.6	55	237
5	Podzol	Dy 4.42	94	0.99	6.4	75	23	33	2.2	87	196
6	Podzol	Dy 5.31	93	0.81	6.1	74	27	25	-2.0	69	192
7	Podzol	Uc 1.21	93	0.60	6.5	63	38	38	2.6	73	168
8	Solodized solonetz	Dy 5.42	97	1.11	6.2	89	64	65	2.2	48	231
9	Solodized solonetz	Dy 5.41	98	0.65	6.7	33	10	28	-0.2	62	230
10	Podzol	Db 3.82	93	1.04	7.2	67	27	20	10.6	100	278
11	Solodized solonetz	Dy 5.22	95	0.74	6.0	52	40	33	11.8	43	232
12	Solodized solonetz	Db 4.21	92	1.42	5.4	162	90	100	24.0	40	288
13	Ground water podzol	Dy 5.42	99	1.64	5.8	32	11	25	-7.0	52	311
14	Podzol	Uc 1.21	92	0.96	6.5	79	17	18	0.6	100	345
15	Podzol	Uc 1.21	96	1.06	6.4	62	16	20	2.0	100	351
16	Ground water podzol	Dy 5.41	94	2.50	6.2	123	7	10	-9.0	34	396
17	Solodized solonetz	Dd 4.42	92	2.52	6.1	99	21	25	0.0	30	462
18	Podzol	Dr 4.42	94	0.78	6.4	24	15	15	-2.0	100	393
19	Ground water podzol	Dy 5.42	92	1.18	6.3	35	17	20	5.2	39	392

^AExperiments were conducted at sites 1-7 in 1971; 8-13 in 1972; and 14-19 in 1973

^BAll values except 'Depth to clay' relate to 0-10 cm depth. See text for descriptions of analytical techniques.

^CLeaching period = period between May and October soil samplings

The soil's phosphorus concentration was determined by digestion for 4 hr with boiling HCl after ashing with magnesium acetate; phosphorus in the digest was measured with an auto-analyser. Organic carbon was measured by the method of Walkley and Black, and pH in a 1:5 suspension of soil in water. "Active" aluminium (hereafter referred to simply as aluminium) was determined by extracting the soil for 6 hr with 0.5M CaCl₂ after removing organic matter with 20% H₂O₂, the aluminium in solution being measured by using alizarin red S with thioglycollic acid (Bond 1957). To determine "active" iron (hereafter iron), peroxidized soil was shaken for 2 hr with a mixture of 0.2M ammonium oxalate and 0.2M oxalic acid at pH 3; the iron in solution was measured by the method of Sandell (1959). Phosphate sorption was determined essentially as described by Ozanne and Shaw (1967). The term P sorption normally refers to the amount of phosphorus sorbed by soil when in equilibrium with a standard solution of phosphorus (1 ppm), determined by interpolation, according to Ozanne and Shaw's method; but where specified a simpler index, namely phosphorus sorbed by shaking soil with a single solution initially containing 3 ppm phosphorus, is indicated.

The phosphorus concentration of the herbage was determined by X-ray spectroscopy.

Phosphate Recovery

For each site the recovery of applied phosphorus at each rate of application was calculated by adding the increase in phosphorus in the top 10 and 30 cm of soil, during the interval between samplings, to the amount of phosphorus measured in the herbage. The relation between the amount of phosphorus applied and the amount recovered in soil and herbage at a site was examined by regression analysis, and where they were significantly correlated ($P < 0.10$) the recovery for an application of 40 kg ha⁻¹ P - 'recovery P₄₀' - was read from the best fitted curve and expressed as a percentage. The 15 measured recoveries for a site were thus

used to provide a single recovery index. The median rate of $40 \text{ kg ha}^{-1} \text{ P}$ was chosen because near this point the fitted curve is statistically most reliable.

Results

Site Characteristics

Values for P sorption, iron and aluminium for soil sampled at 0-10 cm at each site, and for rainfall recorded during the leaching period, that is between initial and final sampling, are shown in Table 1. Several of the characters measured were closely correlated as shown in Table 2.

Phosphorus Recovery

At 16 sites the quantity of phosphorus recovered (0-30 cm) increased linearly with that applied and at three the relation was quadratic (Table 3). Mean recoveries calculated for the 19 sites were linearly related to phosphorus application, the Y intercept being not significantly different from zero (Fig. 2). Values for recovery P_{40} at individual sites varied from 0 to 98% when the top 10 cm of soil was considered, and from 10 to 100% for the top 30 cm (Fig. 3); means were 43% and 60%, respectively. At the remaining 12 sites, phosphorus recovery was not significantly related to application, due undoubtedly to the large errors involved in measuring changes in soil phosphorus in the field. As recovery P_{40} could not be determined at these sites, their results were excluded.

Factors Determining Recovery

Relationships between phosphorus recovery and soil properties can be considered for both 0-10 and 0-30 cm depths. Strongest correlations were obtained between recovery at 0-30 cm and soil properties at 0-10 cm.

Linear correlation coefficients given in Table 2 show that recovery P_{40} , 0-30 cm, was significantly related to iron ($r = 0.76^{***}$), P sorption ($r = 0.75^{***}$) and aluminium ($r = 0.52^*$), measured in the top 10 cm

Table 2. Linear correlation co-efficients between some measured site characters

	Rainfall during leaching period (mm)	pH	Aluminium (mg 100g ⁻¹)	Iron (mg 100 ⁻¹)	P sorption (ug g ⁻¹)
Recovery, P ₄₀ 0-30 cm (%)	0.12	-0.29	0.52	0.76	0.75
Recovery, P ₄₀ 0-10 cm (%)	0.24	-0.33	0.33	0.67	0.62
P sorption	0.13	-0.36	0.71	0.84	-
Iron	0.12	-0.56	0.85	-	-
Aluminium	-0.16	-0.55	-	-	-
pH	-0.21	-	-	-	-

Least significant values for correlation co-efficients were:

P = 0.05, 0.43

P = 0.01, 0.55

P = 0.001, 0.67

Table 3. Equations of best fit relating phosphorus recovery in soil (0-30cm) and harvested herbage to the rate of phosphorus application^A and 'recovery P₄₀' values determined from these equations.

Site No.	Equation	Significance ^B	Recovery P ₄₀ %
1	$y = -23.9 + 2.56x - 0.024x^2$	**	100
2	$y = 8.8 + 0.56x$	***	78
3	$y = 7.6 + 0.48x$	*	67
4	$y = -2.8 + 0.50x$	***	43
5	$y = -6.2 + 0.66x$	***	51
6	$y = -10.6 + 0.85x$	***	59
7	$y = 13.6 + 0.36x$	**	70
8	$y = 13.2 + 0.41x$	**	74
9	$y = 3.5 + 0.31x$	**	40
10	$y = 8.8 + 0.39x$	*	61
11	$y = 8.7 + 0.56x$	***	78
12	$y = -28.2 + 1.74x - 0.008x^2$	***	72
13	$y = -3.0 + 0.52x$	***	45
14	$y = -7.0 + 0.56x$	***	39
15	$y = 12.8 - 0.02x + 0.009x^2$	***	66
16	$y = -17.6 + 0.54x$	*	10
17	$y = 10.2 + 0.32x$	**	58
18	$y = 15.1 + 0.22x$	+	60
19	$y = 8.0 + 0.46x$	***	66
Mean	$y = 1.5 + 0.55x$	***	59

^A At twelve sites there was no significant correlation. These have been omitted (see text).

^B +, $P < 0.10$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Fig. 2. The relationship between phosphorus applied and mean phosphorus recovered in soil (0-30 cm) and harvested herbage at 19 sites.

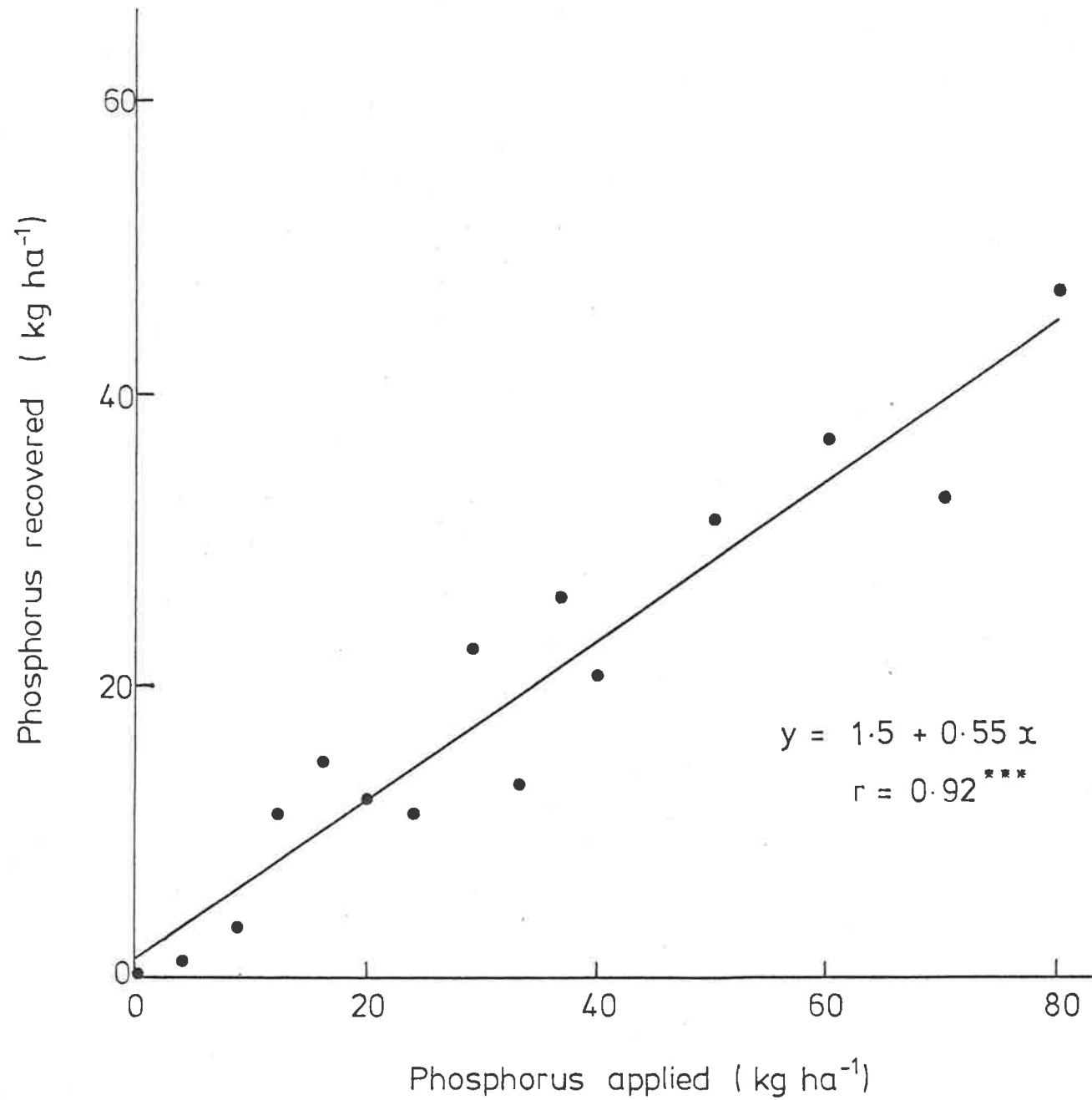
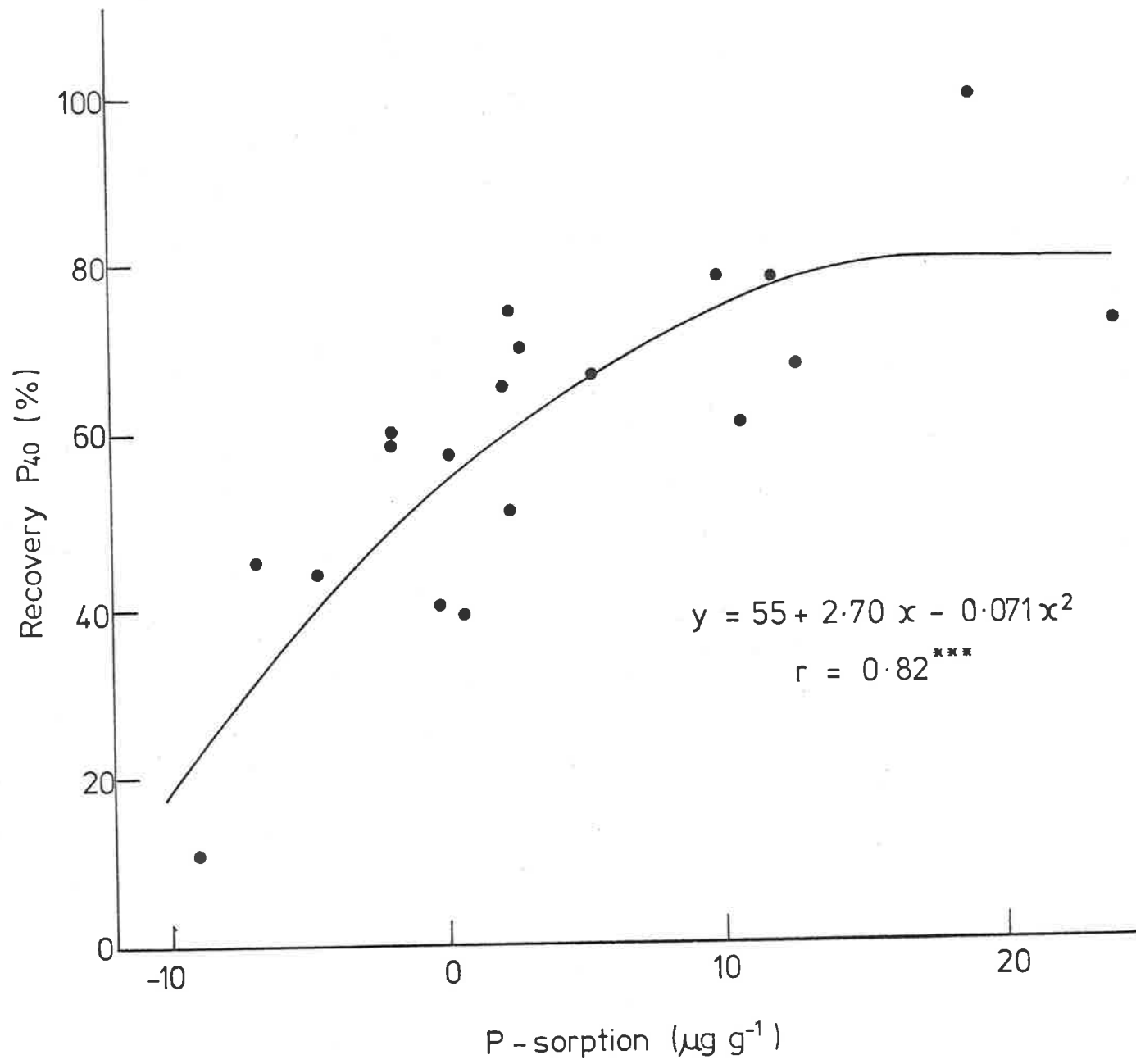


Fig. 3. The relationship between percentage recovery of 40 kg ha^{-1} applied phosphorus in the soil (0-30 cm) and herbage, 5 months after application (recovery P_{40}), and phosphorus sorbed by soil (0-10 cm) in equilibrium with 1 ppm P solution (P sorption).



of soil. The relation with rainfall - either total for the leaching period or for the first month after phosphorus application - was not significant. The correlations are improved by including a quadratic term. Thus, for P sorption ($\mu\text{g g}^{-1}$) (Fig. 3) -

$$\text{Recovery } P_{40} = 55 + 2.70x - 0.071x^2 \quad (r = 0.82^{***}); \dots\dots\dots(1)$$

for iron concentration ($\text{mg } 100 \text{ g}^{-1}$) -

$$\text{Recovery } P_{40} = 28 + 1.41x - 0.0085x^2 \quad (r = 0.81^{***}); \dots\dots\dots(2)$$

and for aluminium ($\text{mg } 100 \text{ g}^{-1}$) -

$$\text{Recovery } P_{40} = 17 + 1.99x - 0.15x^2 \quad (r = 0.69^{**}); \dots\dots\dots(3)$$

Using the simpler P sorption measurement ($\mu\text{g g}^{-1}$),

$$\text{Recovery } P_{40} = 47 + 3.52x - 0.088x^2 \quad (r = 0.81^{***}); \dots\dots\dots(4)$$

Attempts were made to improve further the correlation between phosphorus recovery and measured variables by using multivariate regression analysis with up to four variables. As P sorption, iron and aluminium were themselves closely correlated (Table 2), only one of these variables was included at a time in each regression. Others tested included rainfall (total leaching period and first month only), percent sand, organic carbon, depth to clay, pH and squared values of iron, aluminium and sorption. None of these combinations gave correlations significantly better than those obtained with P sorption or iron alone.

Considering recovery in the top 10cm, the best correlation was obtained with iron concentration, the equation being

$$\text{Recovery } P_{40} = 15.9 + 1.13x - 0.0057x^2 \quad (r = 0.69^{**}); \dots\dots\dots(5)$$

Discussion

Substantial amounts of phosphorus were not accounted for at most of the 19 experimental sites. Phosphorus present in unharvested herbage and roots would account for a small amount - usually less than 5 kg ha^{-1} - of this deficit*. The rest of the unaccounted phosphorus must have been leached

* (1) Approximately 1000 kg ha^{-1} oven-dry herbage was left by the flail mower (Elliott, personal communication); this would contain approximately $2 \text{ kg ha}^{-1} \text{ P}$.

(2) Assuming a 2:1 tops:roots ratio (Troughton 1957) and a phosphorus concentration of 0.15% in roots (Whitehead 1974), these would contain approximately $3 \text{ kg ha}^{-1} \text{ P}$.

beyond the sampling depth, for little newly applied phosphorus is likely to have become insoluble in boiling HCl in 5 months. At the $40 \text{ kg ha}^{-1} \text{ P}$ rate, the mean loss over all sites, allowing for phosphorus present in unharvested herbage and roots, was 40%. Since the average phosphorus recovery for the 19 sites was proportional to the amount applied (Fig. 2), the percentage loss at rates normally applied by graziers ($10\text{-}15 \text{ kg ha}^{-1} \text{ P}$) would be similar.

Such losses occurring within the season in which the superphosphate was applied, and on sites that represent a large area of agricultural land, are agronomically important. The larger losses reported previously in South Australia (Alston and Chin 1974; Clarke 1974) occurred on sites that had much coarser soil and higher rainfall. The leaching reported now would explain the observed lack of phosphorus accumulation in the sub-soil in some areas of the South-East (Lewis & Clarke unpublished data). The problem is unlikely to be solved by applying frequent small superphosphate

dressings because generally a constant proportion of applied phosphorus was leached. Lining may successfully reduce leaching of superphosphate (Clarke 1974), and the use of less soluble fertilizers, such as rock phosphate, may be worthwhile where leaching is most severe, as demonstrated elsewhere by Alston and Chin (1974) and Clarke (1974). However, a more practical solution may be to grow deep rooting species or cultivars that are able to retrieve leached phosphorus and other nutrients.

Within the conditions of these experiments, the ability of the soil to sorb soluble phosphate was clearly the dominating factor determining the extent of leaching, and sorption was a function of the soil's concentrations of reactive iron and aluminium. At a given time the amount of phosphorus that can be leached depends on the concentration of phosphate ions in the soil solution, which at equal phosphorus dressings is determined by the phosphorus sorption isotherm. As rainfall during the leaching period did not affect leaching losses, even though it varied three-fold in different experiments, it appears that even the lightest rainfall removed unsorbed phosphorus, and sorbed phosphorus was released to the soil solution so slowly that further rain caused little extra leaching. This agrees with the observation that most phosphorus is leached soon after soluble phosphate is applied (Alston and Chin 1974; Clarke 1974). The leaching of phosphorus can be compared with that of gypsum, which according to Millington and Powrie (1968) is often controlled by the rate of its dissolution and diffusion into the percolating water stream and not by the amount of water passing through the soil.

It is not known why soil properties measured at 0-10 cm depth explain phosphorus retention at 0-30 cm more accurately than retention at 0-10 cm. Some phosphorus was retained at 10-30 cm in these experiments, unlike those of Clarke (1974), but again retention at 0-30 cm was only poorly related to soil properties at that depth. Iron was at least as important as aluminium in determining both sorption and retention of phosphorus. Ozanne et al (1967)

found that retention in West Australian soils was related significantly to aluminium but not to iron, and Yuan and Breland (1969) and Ballard and Fiskell (1974) showed sorption to be more closely correlated with aluminium. Different extraction techniques, however, were used by the different authors.

For practical agronomic purposes it is desirable to be able to predict leaching losses for a given soil, especially when using the 'balance sheet' method for estimating superphosphate requirements (Lewis and Clarke 1975). Equation (4) indicates that a fair estimate of likely short term losses can be made for sandy soils in this region by applying a simple sorption test to samples of top soil. If necessary such estimates could be made on a survey scale with minimal effort.

Acknowledgements

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APPENDIX 4

The basic data from which the regression equations were derived are presented in the following Tables. Data have not been transformed to kg ha^{-1} .

TABLE 26

Summary of soil analyses, Hundred of Coles.

Site No.	Total phosphorus (ppm)				Organic phosphorus (ppm)	
	0-10 cm	10-30 cm	30 cm - c	c	0-10 cm	10-30 cm
1	89	43	33	77	34	17
2	110	47	40	75	52	19
3	44	29	31	62	24	9
4	64	35	27	60	34	13
5	132	38	40	66	59	14
6	79	36	37	70	29	13
7	37	25	30	67	8	7
8	103	37	34	69	48	14
9	-	-	-	-	-	-
10	88	33	30	52	37	12
11	52	33	29	65	16	11
12	66	34	30	63	31	12
13	74	38	40	65	31	14
14	100	37	60	83	55	14
15	88	55	60	87	52	24
16	68	45	46	79	23	8
17	70	50	47	79	36	11
18	81	51	40	79	52	22
19	42	33	34	68	9	11
20	140	50	46	75	77	21
21	88	45	40	85	44	18
22	102	51	53	89	56	22
23	56	34	34	78	25	12
24	96	46	53	82	49	19
25	84	44	60	77	39	18
26	61	38	37	73	30	14
27	76	46	46	66	39	19
28	89	42	57	76	45	17
29	66	33	30	62	31	11
30	88	43	48	63	39	17

TABLE 26 (cont.)

Site No.	Available phosphorus (ppm)		Total Sulphur (ppm)			
	Spring	Autumn	0-10 cm	10-30 cm	30cm - c	c
1	11.1	13.9	180	98	64	182
2	12.9	9.6	206	96	93	199
3	3.4	2.4	141	92	10	207
4	8.9	6.7	167	94	92	192
5	16.3	11.3	245	90	75	152
6	9.7	7.5	162	77	78	204
7	2.6	2.0	102	70	73	181
8	10.8	7.7	234	101	92	256
9	-	-	-	-	-	-
10	16.0	18.0	180	88	82	209
11	7.0	8.7	128	87	82	192
12	8.0	-	161	90	80	180
13	10.3	-	155	87	98	211
14	11.0	10.3	246	108	118	232
15	9.5	7.9	182	97	124	225
16	7.5	9.6	121	83	113	215
17	8.9	7.3	132	89	134	200
18	9.5	7.3	209	112	93	221
19	2.6	1.9	121	80	79	245
20	15.8	14.8	305	118	111	219
21	10.4	8.2	192	105	83	190
22	15.6	-	221	104	115	252
23	5.9	-	163	117	113	253
24	12.5	-	202	95	149	232
25	10.2	-	171	95	88	187
26	5.9	6.1	156	95	130	214
27	6.7	5.2	206	107	105	228
28	7.0	7.2	225	115	104	181
29	8.8	10.5	168	95	73	200
30	11.3	-	205	107	109	161

TABLE 26 (cont.)

Site No.	Organic carbon (percent)		Total calcium (ppm)	Total potassium (ppm)	c.e.c. (m.e. 100 g ⁻¹)	
	0-10 cm	10-30 cm	0-10 cm	0-10 cm	0-10 cm	10-30 cm
1	1.58	0.64	680	710	5.3	3.3
2	1.68	0.53	1150	1280	6.2	2.5
3	1.04	0.43	440	710	3.8	1.9
4	1.31	0.48	530	680	4.6	2.6
5	1.38	0.35	960	1820	4.7	1.9
6	1.24	0.40	530	1290	3.6	1.9
7	0.74	0.25	330	1400	3.0	1.7
8	1.43	0.35	950	740	5.4	2.2
9	-	-	-	-	-	-
10	1.39	0.38	830	550	4.5	1.9
11	1.10	0.42	620	1190	4.5	2.1
12	1.15	0.34	480	1320	2.8	1.0
13	1.23	0.48	690	1040	3.3	1.9
14	1.79	0.54	760	710	4.7	1.9
15	1.29	0.36	500	1300	3.2	1.6
16	0.88	0.44	510	820	3.0	1.6
17	1.12	0.51	460	560	2.8	1.4
18	1.56	0.57	500	560	3.4	1.7
19	0.94	0.43	340	740	2.2	1.4
20	1.85	0.40	1090	1810	5.3	1.6
21	1.36	0.45	540	920	2.5	1.3
22	1.50	0.36	520	1470	3.1	1.6
23	1.13	0.56	430	710	3.0	1.7
24	1.23	0.33	600	750	3.8	1.7
25	1.20	0.42	460	490	2.8	1.6
26	1.21	0.45	620	720	3.6	1.8
27	1.31	0.52	540	830	3.7	1.9
28	1.70	0.58	710	490	5.2	2.4
29	1.06	0.41	570	870	3.6	2.1
30	1.31	0.56	560	660	4.0	2.8

TABLE 26 (cont.)

Site No.	Total nitrogen (percent) 0-10 cm	pH			
		0-10 cm	10-30 cm	30 cm - c	c
1	.214	6.1	6.15	6.4	6.1
2	.259	6.35	6.55	6.7	7.2
3	.162	6.4	6.65	6.85	7.35
4	.181	5.95	6.3	6.55	6.65
5	.245	6.5	6.65	7.1	7.35
6	.199	5.8	6.3	6.65	6.9
7	.133	6.4	6.8	6.85	6.85
8	.250	6.2	6.65	6.95	7.3
9	-	-	-	-	-
10	.208	6.25	6.55	6.85	7.55
11	.173	6.3	6.7	6.85	7.05
12	.186	5.95	6.55	6.85	7.3
13	.203	6.3	6.4	6.45	6.3
14	.283	5.75	6.25	6.45	6.65
15	.205	6.0	6.35	6.35	6.4
16	.136	6.25	6.45	6.5	6.05
17	.177	5.9	6.3	6.35	6.15
18	.248	5.8	6.2	6.65	7.25
19	.145	6.25	6.5	6.65	6.7
20	.296	5.6	6.1	6.7	6.7
21	.200	5.95	6.3	6.65	6.4
22	.223	5.65	6.2	6.4	6.95
23	.158	6.1	6.55	6.6	6.45
24	.186	6.05	6.55	6.75	7.35
25	.174	6.0	6.3	6.55	7.4
26	.160	6.25	6.5	6.5	6.45
27	.190	6.0	6.25	6.6	7.05
28	.228	5.95	6.25	6.45	6.5
29	.146	6.3	6.6	6.75	6.3
30	.173	6.0	6.15	6.35	6.45



TABLE 27

Summary of soil analyses, Hundred of Willalooka.

Site No.	Total phosphorus (ppm)				Organic phosphorus (ppm)	
	0-10 cm	10 - 30 cm	30 cm - c	c	0-10 cm	10 - 30 cm
1	107	40	42	57	43	18
2	116	43	35	54	49	10
3	142	46	41	64	56	12
4	34	25	29	66	6	1
5	89	38	33	63	32	8
6	148	50	40	62	67	14
7	81	41	33	62	31	9
8	95	39	33	65	33	8
9	52	32	31	70	13	5
10	125	50	40	73	50	14
11	101	46	44	55	44	16
12	98	41	39	68	36	9
13	73	35	32	59	27	6
14	110	45	48	66	38	11
15	35	33	31	71	5	5
16	131	52	52	84	66	15
17	120	49	39	63	46	13
18	66	31	30	64	21	4
19	62	27	30	46	20	2
20	76	35	32	50	29	6
21	126	46	36	49	53	12
22	98	34	32	66	39	6
23	62	36	36	53	11	7
24	36	29	28	64	5	3
25	120	48	38	70	48	13
26	138	47	40	75	59	12
27	-	-	-	-	-	-
28	96	47	35	61	35	12
29	111	49	45	69	41	14
30	125	50	47	75	53	14

TABLE 27 (cont.)

Site No.	Available phosphorus (ppm)		Total sulphur (ppm)			
	Spring	Autumn	0-10 cm	10-30 cm	30cm - c	c
1	16.7	11.2	180	78	82	172
2	16.2	13.2	182	78	71	135
3	32.5	23.4	195	87	82	165
4	2.1	3.0	96	62	57	181
5	15.0	13.8	145	85	73	205
6	17.8	13.8	242	89	61	136
7	14.1	11.6	144	81	73	154
8	16.5	11.6	147	77	73	170
9	5.2	5.8	108	77	71	140
10	20.2	11.6	211	85	66	154
11	15.4	10.7	194	97	77	147
12	14.9	10.0	168	84	77	189
13	9.7	8.1	141	84	71	141
14	15.0	10.4	182	87	84	158
15	2.0	2.3	80	77	77	197
16	21.6	24.1	228	97	116	210
17	14.3	10.3	209	95	76	152
18	12.7	11.4	103	74	75	223
19	16.3	-	82	57	55	84
20	21.3	-	95	63	53	84
21	35.1	-	153	68	55	80
22	13.5	11.6	137	68	47	96
23	12.0	10.1	75	58	53	72
24	2.5	2.7	74	61	51	121
25	15.2	13.0	147	71	51	132
26	14.5	12.5	236	88	81	193
27	-	-	-	-	-	-
28	18.9	17.5	132	72	60	106
29	16.1	11.4	185	89	71	128
30	20.2	19.5	188	85	72	178

TABLE 27 (cont.)

Site No.	Organic carbon (percent)		Total calcium (ppm) 0-10 cm	Total potassium (ppm) 0-10 cm	c.e.c (m.e. 100 g ⁻¹)	
	0-10 cm	10-30 cm			0-10 cm	10-30 cm
1	1.03	0.22	710	3000	3.2	0.8
2	1.11	0.23	850	3520	4.2	1.9
3	1.09	0.23	900	3980	4.8	1.6
4	0.67	0.23	590	2870	3.3	1.7
5	1.00	0.29	770	2720	4.0	1.6
6	1.42	0.39	1100	3350	5.2	2.3
7	0.78	0.20	650	3160	3.7	2.0
8	0.78	0.29	710	3050	4.1	2.6
9	0.68	0.25	700	3570	3.6	2.1
10	1.23	0.32	820	2820	4.4	1.5
11	1.27	0.40	720	2460	4.1	1.7
12	1.16	0.31	720	3120	4.1	2.2
13	0.92	0.27	700	2400	4.2	2.2
14	1.23	0.32	800	2850	4.8	2.5
15	0.51	0.20	450	2890	2.7	1.4
16	1.47	0.26	850	2600	4.5	1.5
17	1.45	0.36	850	2660	4.9	2.0
18	0.71	0.30	490	2700	2.6	1.4
19	0.58	0.20	590	1680	2.9	1.7
20	0.65	0.22	660	2280	3.0	1.3
21	0.90	0.26	970	2310	3.9	1.6
22	0.93	0.22	870	3050	3.9	1.3
23	0.45	0.18	950	4140	3.1	2.1
24	0.48	0.16	480	2940	2.4	1.6
25	1.00	0.27	740	3430	3.7	1.5
26	1.49	0.34	1030	2940	5.2	1.9
27	-	-	-	-	-	-
28	0.90	0.29	850	5380	4.4	2.2
29	1.23	0.31	770	4400	4.3	1.8
30	1.11	0.26	820	3020	4.2	1.5

TABLE 27 (cont.)

Site No.	Total nitrogen (percent) 0-10 cm	pH			
		0-10 cm	10-30 cm	30 cm - c	c
1	.100	6.2	6.35	6.6	7.3
2	.103	6.45	6.55	6.8	6.95
3	.104	6.2	6.7	6.85	7.3
4	.050	6.6	6.9	7.05	7.5
5	.087	6.1	6.55	7.2	7.95
6	.145	5.9	6.4	6.8	8.2
7	.089	6.5	6.8	7.15	7.5
8	.087	6.4	6.8	7.05	7.5
9	.040	6.65	6.8	7.0	6.9
10	.131	6.1	6.6	6.6	6.85
11	.125	5.95	6.2	8.0	
12	.092	6.15	6.45	6.75	7.6
13	0.73	6.7	6.9	7.0	7.45
14	.109	6.05	6.4	6.7	7.65
15	0.29	6.75	6.95	7.15	7.5
16	.137	6.1	6.50	6.8	7.9
17	.137	6.2	6.55	7.1	8.75
18	.053	6.6	6.85	7.2	7.9
19	.050	6.95	6.9	7.0	7.45
20	.057	6.65	6.75	6.6	7.50
21	.095	6.5	6.45	6.4	6.9
22	.094	6.45	6.5	6.6	6.7
23	.033	7.05	6.8	7.2	7.25
24	.035	6.6	6.75	6.7	7.25
25	.101	5.8	6.1	6.65	7.35
26	.170	5.8	6.1	6.8	8.5
27	-	-	-	-	
28	.083	6.3	6.55	6.9	7.25
29	.128	5.9	6.3	6.75	7.4
30	.118	6.1	6.35	6.65	7.45

TABLE 28

Summary of soil analyses, Hundred of Senior.

Site No.	Total phosphorus (ppm)				Organic phosphorus (ppm)	
	0-10 cm	10-30 cm	30 cm - c	c	0-10 cm	10-30 cm
1	90	39	29	47	31	6
2	87	41	39	64	33	6
3	67	36	33	55	26	4
4	83	43	40	64	34	7
5	42	36	25	58	7	4
6	75	33	27	69	13	3
7	83	29	28	81	22	3
8	87	39	30	93	24	6
9	88	43	31	83	29	7
10	67	38	30	78	26	5
11	41	30	28	78	4	2
12	110	39	35	75	35	6
13	83	35	30	77	27	4
14	41	33	34	62	8	3
15	108	45	41	75	38	8
16	105	52	44	72	32	11
17	120	53	44	80	36	11
18	106	54	44	90	31	12
19	-	-	-	-	-	-
20	48	30	30	59	9	2
21	95	41	38	70	30	6
22	78	39	34	78	22	6
23	82	43	31	59	27	7
24	71	36	30	61	22	4
25	122	59	50	71	39	14
26	44	41	32	54	7	6
27	97	44	49	78	28	8
28	96	43	38	72	20	7
29	62	32	30	72	16	3
30	38	30	27	64	7	2

TABLE 28 (cont.)

Site No.	Available phosphorus (ppm)		Total sulphur (ppm)			
	Spring	Autumn	0-10 cm	10-30 cm	30cm - c	c
1	20.8	13.7	128	51	40	90
2	14.4	8.7	139	73	52	103
3	11.6	12.0	109	73	61	99
4	14.1	8.7	135	75	52	139
5	8.3	5.3	63	48	35	116
6	19.5	14.7	86	49	37	103
7	20.4	14.9	98	48	40	146
8	11.3	9.9	132	60	40	159
9	14.8	15.3	117	62	35	146
10	10.5	9.7	101	56	44	147
11	2.1	2.0	69	41	35	114
12	18.7	18.4	135	54	41	130
13	11.3	9.0	124	50	36	157
14	2.5	2.2	71	67	63	102
15	13.8	13.1	140	62	49	143
16	17.6	18.1	143	72	63	136
17	20.5	17.9	158	69	64	173
18	19.3	17.4	158	76	64	139
19	-	-	-	-	-	-
20	12.8	9.0	77	60	56	106
21	12.5	9.8	147	61	52	116
22	14.3	12.5	98	53	46	131
23	7.9	7.9	116	55	40	101
24	11.7	9.8	102	57	42	124
25	21.8	19.2	169	72	65	121
26	6.9	4.9	72	66	59	121
27	11.8	12.5	138	83	68	124
28	17.3	17.2	116	73	68	133
29	15.3	13.3	84	66	58	153
30	2.7	2.8	71	67	56	94

TABLE 28 (cont.)

Site No.	Organic carbon (percent)		Total calcium (ppm) 0-10 cm	Total potassium (ppm) 0-10 cm	c.e.c. (m.e. 100 g ⁻¹)	
	0-10 cm	10-30 cm			0-10 cm	10-30 cm
1	0.76	0.21	840	2390	3.1	1.5
2	0.86	0.16	700	2820	2.9	1.0
3	0.69	0.19	600	2480	2.0	0.9
4	0.87	0.22	590	2480	2.8	1.7
5	0.35	0.13	570	3050	2.4	1.4
6	0.48	0.16	620	2790	2.2	1.1
7	0.50	0.17	600	2670	1.8	0.9
8	0.73	0.21	600	2890	1.9	0.8
9	0.72	0.17	690	2700	2.2	1.3
10	0.69	0.19	720	2780	2.9	1.6
11	0.33	0.16	500	4010	1.8	1.2
12	0.70	0.20	720	2530	2.6	1.2
13	0.61	0.25	760	3380	2.4	1.2
14	0.37	0.17	420	2370	1.2	0.5
15	0.89	0.26	750	3160	2.6	1.6
16	0.91	0.20	730	2500	3.3	1.9
17	0.89	0.26	740	2720	3.3	1.6
18	0.93	0.25	650	2450	3.0	1.1
19	-	-	-	-	-	-
20	0.46	0.15	660	2670	1.8	1.4
21	0.82	0.24	630	2240	3.0	1.8
22	0.50	0.17	600	2500	2.8	1.5
23	0.74	0.18	680	2710	2.7	1.3
24	0.71	0.24	690	2600	2.5	1.2
25	1.07	0.22	800	1940	3.1	1.2
26	0.46	0.16	550	3540	2.1	1.5
27	0.88	0.25	770	3190	3.7	2.2
28	0.68	0.21	570	2930	2.7	1.4
29	0.58	0.21	570	2500	2.5	1.2
30	0.51	0.18	600	3070	2.5	1.1

TABLE 28 (cont.)

Site No.	Total nitrogen (percent) 0-10 cm	pH			
		0-10 cm	10-30 cm	30cm - c	c
1	.149	6.9	6.9	7.5	7.9
2	.157	6.3	6.55	6.6	7.0
3	.126	6.6	6.5	6.75	6.8
4	.159	6.1	6.35	6.7	7.5
5	.083	7.55	7.15	7.4	7.9
6	.088	6.95	6.95	7.0	7.7
7	.108	6.8	6.75	6.85	7.55
8	.140	6.3	6.5	6.85	7.75
9	.128	6.5	6.7	6.85	7.5
10	.103	6.65	6.85	7.25	7.85
11	.063	6.7	6.8	7.05	7.4
12	.125	6.45	6.75	6.95	7.8
13	.118	6.75	7.0	7.1	7.65
14	.067	7.0	6.95	7.0	6.7
15	.133	6.5	6.6	6.95	8.2
16	.142	6.35	6.8	7.2	8.4
17	.138	6.4	6.45	6.6	7.3
18	.142	6.2	6.2	6.4	6.8
19	.170	6.3	6.4	6.7	8.3
20	.068	7.35	7.3	7.2	7.7
21	.138	6.3	6.75	6.95	7.65
22	.094	7.05	7.1	7.3	7.7
23	.115	6.6	6.6	7.3	7.8
24	.137	6.85	6.9	7.15	7.6
25	.211	6.35	6.65	6.6	7.3
26	.115	6.7	6.9	7.25	7.8
27	.184	6.45	6.75	6.9	7.7
28	.168	6.6	6.45	6.55	7.6
29	.132	6.5	6.7	6.95	7.7
30	.104	6.75	6.9	7.1	7.8

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