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Potassium release and fixation in OHIO SOILS as measured by cropping and chemical extraction

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POTASSIUM RELEASE AND FIXATION IN OHIO SOILS AS MEASURED BY CROPPING AND CHEMICAL EXTRACTION

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The use of potassium bearing fertilizers is a generally accepted practice by the farmers of Ohio. It is also generally recognized and accepted that soils differ rather markedly in their requirement for additional potassium, K.[2] Yet little direct information has been available regarding the specific needs for K on the major soils of Ohio when subjected to prolonged intensive cropping.

Most soils contain from 30,000 to 60,000 pounds of total K per 2,000,000 pounds of topsoil. Crops usually require from 50 to 250 pounds per acre per year depending on kind of crop and yield. Hence, the problem of K fertility is one of low availability of that which is present.

The "available"K obtained by soil tests represents the exchangeable K which is extracted from the soil with a suitable salt solution. Even though exchangeable K is available to plants, this does not mean that they will take up all of the K immediately since their roots do not contact all of the soil.

Exchangeable K tends to be in chemical equilibrium with nonexchangeable K which is not immediately available to plants. A schematic diagram of the various aspects of K equilibria in soils has been prepared and included in Figure 1 as an aid to a clearer presentation of the problem and the results obtained. With the exception of making a distinction between the two forms of fixed K (wet and dry fixed) by means of nitric acid extraction recently proposed by the present authors (2), these interrelationships are not new but are old, generally accepted phenomena.

[1]The authors wish to express their appreciation to Drs. G. W. Volk, P. F. Pratt, C. E. Evans and H. J. Mederski, who contributed to certain phases of these studies.

[2]The symbol K will be used herein to designate the chemical element potassium.

When soluble K fertilizer is applied to the soil, very little of it remains in the soil solution. Most of it goes to exchangeable form, and some of it then goes on over to nonexchangeable form. It is possible that some of it also goes directly from soluble K to nonexchangeable K. If exchangeable K is removed by cropping or leaching, there will be a tendency for more K to become exchangeable from nonexchangeable form. Whether a soil under cropping can maintain its level of exchangeable K depends upon the relative rates of removal and recovery from nonexchangeable form. The rate of removal varies greatly depending upon type of crop and intensity of cropping. Likewise, the rate of recovery varies tremendously with the type of soil. If the exchangeable K level is high, a crop (or several crops) may obtain adequate K without any renewal of the exchangeable from the nonexchangeable form. The crop would simply decrease the level of exchangeable K by the amount it took up. If the exchangeable K is high and the rate of renewal of K from nonexchangeable form is only moderate, the crop could still obtain the K required from the reservoir of exchangeable K with the latter decreasing in an amount considerably smaller than the crop removed.

In both of the cases described above (plants growing on soils high in exchangeable K), it is not likely that these crops would yield more if K were applied. However, if this greater removal than recovery from nonexchangeable form continued indefinitely; such a soil, regardless of its initial high level of exchangeable K, would eventually need K fertilization to maintain a level of available K adequate for plant growth. The alternative would be decreased yields due to smaller supply of available K for the crop.

If the available level of K in a given soil is low, this generally means that the rate of conversion to available form is too low to maintain an adequate level of available K. It probably also means that, if the intensity of cropping is to be maintained, most of the K required by the crops will have to be supplied from a supplemental source such as fertilizer, manure, or crop residues.

From the above, it is evident that the level of available K as revealed by soil tests is very important as a source of K for the crop's immediate requirement. However, the need for information on rates of conversion from unavailable to available forms in the soils of Ohio is also obvious.

Chemical extraction using one normal boiling nitric acid (113° C. for 25 minutes) was used by Pratt and Morse (3) for testing the K released from exchangeable and nonexchangeable forms in a large number of Ohio soils. The K released from nonexchangeable form by this boiling acid extraction has generally been found to be a fairly good guide to the K supplying power of soils under conditions comparable to those used in the greenhouse phase of these studies (2)[3]. The present investigation permitted further correlation between the amounts removed by nitric acid extraction and those removed by cropping in the greenhouse.

Specifically, the objectives of the present investigation were to determine by chemical extraction and by cropping the relative rates of fixation and release of applied and native K in Ohio soils, to correlate the amounts of K removed from the soils with boiling HNO_3 with those removed by repeated salt extraction or by cropping, to assess the value of soil tests for indicating available K in soils, and to attempt to determine specific needs of certain major Ohio soils for K.

MATERIALS AND METHODS

Thirteen representative soils of Ohio were selected and cropped in the greenhouse. Not all of the soils were cropped at any one time. Some of the initial studies were made some time ago, while others were completed only recently. In a few cases samples of soil from the earlier investigations were not available for as complete analysis as was made on those studied more recently.

Exchangeable cations were determined by extraction with neutral normal ammonium acetate solution in the usual way, followed by analysis in the Beckman D. U. flamephotometer. Cation exchange capacities were determined by distillation and measurement of the released NH_3 from ammonium acetate leached soils. Potassium released from nonexchangeable form by boiling nitric acid was determined by the method of Pratt and Morse (3). That released from nonexchangeable from by plants was computed by the following formula: K released = K content of crops minus the sum of the decrease in exchangeable K and the K added as fertilizer. The K content of crops was determined as follows: each cutting was dried,

[3]For a separate listing of the various workers reporting such results, see our paper (2). Since this paper lists most of the pertinent references or cites review articles which do, it does not seem necessary to repeat those references here.

ground and weighed; a sample was ashed or acid digested and the K determined with a Beckman D. U. flamephotometer; and the total K per cutting, as well as that for all cuttings for each treatment, was then computed. All crop data reported herein are the average of three replications of treatments, and practically all of the results are the average of nine consecutive cuttings. Crops grown in the greenhouse had water added as required and nitrogen and phosphate supplied in solution in quantities considered adequate for vigorous growth. Cuttings were removed when a small fraction of the plants began to bloom.

DESCRIPTION OF SOILS USED IN POTASSIUM STUDIES

1. Wooster silt loam pH 6—originally strongly acid, Gray-Brown Podzolic soil, relatively low potassium reserve, sampled on the Snyder Farm Ohio Agricultural Experiment Station, Wooster, Ohio. This soil came from range II of the old legume-soil reaction experiment where the soil was maintained at about pH 6 for approximately 10 years prior to sampling in 1945.
2. Wooster silt loam pH 7—same as above except this soil came from range III of the old legume-soil reaction experiment where the soil was maintained at about pH 7 for approximately 18 years prior to sampling in 1945.
3. Wooster silt loam pH 7.5—same as No. 1 above except soil maintained at pH 7.5 for about 18 years prior to sampling in 1945.
4. Wooster silt loam—same as No. 1 above except this soil was composited from soils Nos. 2 and 3 after they were initially cropped in the greenhouse without K treatment and then moist fallowed for several months.
5. Newton sand—acid Humic Gley soil of course texture relatively low potassium reserve, sampled in Sandusky County in 1952.
6. Toledo silty clay—neutral Humic Gley soil of Lacustrine (lake-laid) origin, fine textured, poorly drained, very high potassium reserve, sampled in Sandusky County in 1952.
7. Clermont silt loam pH 7—acid Planasol derived from Illinoian glaciation, very low in potassium reserve, maintained in experimental plots at pH 7 from 1934 to sampling date, sampled in Clermont County in 1945.
8. Clermont silt loam—soil similar to No. 7, except it was taken from another field and had a pH 5.7 when sampled in 1956.

9. Crosby silt loam pH 7—slightly acid Gray-Brown Podzolic soil from high-lime late Wisconsin till, low medium in potassium reserve, maintained in experimental plots at pH 7 from 1934 to sampling date, sampled in Madison County in 1945.
10. Mahoning silt loam pH 7—strongly acid Gray-Brown Podzolic soil from low-lime late Wisconsin till, low in potassium reserve, maintained in experimental plots at pH 7 from 1934 to sampling date, sampled in Trumbull County in 1945.
11. Rossmoyne silt loam—acid Gray-Brown Podzolic soil, low in potassium reserve, sampled in Brown County in 1956.
12. Brookston silty clay loam—Humic Gley soil from calcareous parent material, high in potassium reserve, sampled in Franklin County in 1956.
13. Hoytville silty clay loam—Humic Gley soil from lacustrine parent material, high in potassium reserve, sampled in Wood County in 1956.

RESULTS AND DISCUSSION

I. A Resume of the Results Obtained—K Equilibria in Soils in Relation to Plant Availability and Chemical Extraction (see Figure 1).

1. Chemical analysis of soil revealed great differences in the amount of exchangeable cations and of boiling acid releasable K in the various Ohio soils (see Table 1).
2. Application of K to soil resulted in a portion remaining exchangeable, a portion being fixed in the moist soil; and, if dried, another portion being fixed in another form by the drying process (see Table 2).
3. Native exchangeable K was found to be a good source of available K to plants (see Table 3).
4. Applied K (much of which remained exchangeable) was also found to be a ready source of available K to plants (see results in Tables 4, 5, and 6).
5. Exchangeable K may be formed by release from non-exchangeable form. This was demonstrated by repeated leaching of the same soil after intervals of time (see Table 7) and by prolonged cropping without further addition of K to the soil i.e., residual effects (see Table 8).
6. K which was fixed by drying was largely available to crops under intensive cropping (see Table 9).

7. Nitrogen, phosphorus, and lime stimulated plants and thus affected their K needs (Table 10).
8. Greenhouse studies are not strictly comparable with field studies because certain factors are not controlled in the field but are in the greenhouse. When a field soil failed to give an expected response to applied K, there was the possibility that the subsoil was contributing additional K to the alfalfa (see Table 11).

II. Discussion of the Results Obtained

A. **Laboratory analysis of soils investigated.** Several chemical properties of the 13 Ohio soils used in these studies are summarized in table 1. Both exchangeable K and K released with boiling nitric acid varied ten fold i.e., 49 to 496 and 190 to 1968 lb/A, respectively from one extreme to another in the range of soils included. From the schematic diagram in figure 1, it is evident that soils high in K release, such as the Hoytville and Toledo, would be expected to release enough K to exchangeable form to supply the crop's need for K. Even under extended intensive cropping such soils would not be expected to require additional K to supply the needs of the crop.

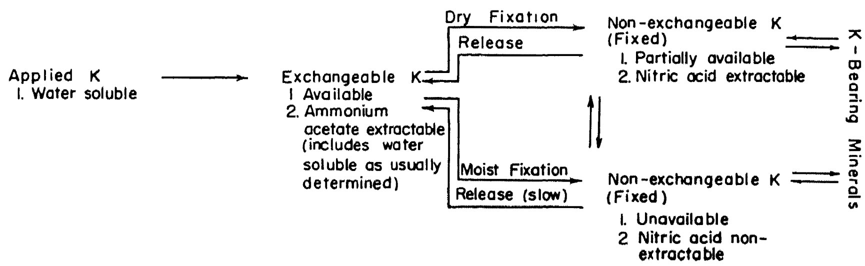

Figure 1. Potassium equilibria in soils

In contrast, a soil like the Clermont, which has very little K release to supplement the exchangeable K, would be expected to need additional K very soon if the K requirement of the crop is to be met. It is evident that a soil like Crosby, which had about the same amount of exchangeable K as the Clermont soils but which had nearly three times as much reserve K, can be expected to supply more of the K requirement of the crop than the Clermont soils. These expectations were borne out in the studies and will be described further in the appropriate sections.

TABLE 1.—The pH, cation exchange capacity, exchangeable cations, and potassium released with boiling 1N HNO_3 of the soils used in these studies

Soil Type	pH*		Exchangeable Cations				K released‡ lb/A
		C.E.C.† me/100g.	Ca me/100g.	Mg me/100g.	K me/100g.	K lb/A	
Clermont silt loam pH 7.0§	7.0	----	----	----	0.14	109	190
Clermont silt loam	5.2	10.88	3.70	2.04	0.18	137	207
Wooster silt loam	6.3	7.98	3.65	1.32	0.06	49	319
Newton sand	5.5	14.44	5.80	4.01	0.12	92	340
Mahoning silt loam pH 7.0§	7.0	----	----	----	0.16	127	426
Wooster silt loam pH 6.0§	5.8	----	----	----	0.15	121	434
Wooster silt loam pH 7.0§	7.1	----	----	----	0.15	119	434
Wooster silt loam pH 7.5§	7.7	----	----	----	0.16	125	434
Rossmoyne silt loam	5.3	12.40	4.55	1.68	0.26	205	435
Crosby silt loam pH 7.0§	7.0	----	----	----	0.18	137	564
Brookston silty clay loam	5.8	26.99	11.40	5.07	0.34	262	874
Hoytville silty clay loam	5.6	23.62	9.50	4.54	0.59	464	1560
Toledo silty clay	5.5	23.64	6.00	6.64	0.64	496	1968

* pH determined with glass electrode using soil:water ratio 1:1 by weight.

†Cation exchange capacity in milliequivalents per 100 grams of dry soil determined by saturation with NH_4^+ followed by Kjeldahl distillation.

‡K released = total K extracted with 1N boiling HNO_3 minus exchangeable K, each in lb/2,000,000 lb. of soil.

§These soils were maintained at the indicated approximate pH values prior to sampling. Since they were cropped at an earlier date, samples were not available for complete analysis.

B. **Fate of K applied to soils.** This phase of the study was reported elsewhere (2). The data for two of the ten soils studied are included in Table 2 to illustrate the kind of results obtained. When K was added to the moist soils and allowed to equilibrate for a few days, analysis showed a certain fraction was exchangeable; but another fraction was fixed in non-exchangeable form. Drying the soils in the oven at 105° C. for at least 24 hours fixed still more of that previously exchangeable. Extraction of the moist soil with one normal boiling

TABLE 2.—Exchangeable, fixed, and acid released K in moist and dried soils at various rates of applied K

Soil Type	K added	Soils Kept Moist			Soils Dried @ 105° C.		
		Exch. K*	Fixed K†	Re-leased K‡	Exch. K*	Fixed K§	Re-leased K‡
	lb/A	lb/A	lb/A	lb/A	lb/A	lb/A	lb/A
Wooster silt loam	0	53	----	353	52	1	348
	37	78	12	358	76	2	364
	74	103	24	365	76	27	404
	390	400	43	392	232	168	512
	780	720	113	456	420	300	700
	1560	1460	129	396	934	550	794
Hoytville silty clay loam	0	464	----	1560	498	(34)	1598
	37	469	32	1635	488	(19)	1672
	74	494	44	1662	530	(36)	1662
	390	720	134	1476	564	156	1772
	780	1000	244	1816	654	346	1930
	1560	1672	352	1760	840	832	2200

*Exchangeable K is that obtained by leaching with neutral normal ammonium acetate.

†Fixed K is that applied but unaccounted for as exchangeable K i.e., applied K— Increase in exchangeable K.

‡Released K is that obtained by extraction with boiling normal nitric acid minus the exchangeable K.

§Fixed K in the dried soils is the amount of decrease in exchangeable K due to the drying; therefore, it is in addition to the K fixed in the moist soil. Figures in parenthesis indicate K was released, not fixed, by drying this soil at zero and very low rates of K application.

nitric acid by the method of Pratt and Morse (3) indicated that little of the K fixed in the moist soil was released by the acid. On the other hand, acid extraction of the dried soils released most of the K fixed by the drying. Since acid released K has been shown by many (2) to be a good index of K supplying power of soils, it was postulated (2) that the K fixed by drying would be available to crops under intensive cropping. Results of a study which tends to substantiate this hypothesis are presented in section G below.

C. **Native exchangeable K as a source of available K to plants.** The results summarized in Table 3, based on studies of 24 soils (some of the data are from the same soils after a sequence of treatments and cropping), indicate a highly significant correlation between exchangeable K and the response of alfalfa to applied K. These data are plotted in Figure 2 so that the shape of the resulting curve can be observed. It will be noted that the relationship between increased yield and soil test value is not a straight line, but is curved. It is evident that a given decrease in the average amount of K available in the range of low test values would be expected to bring about a greater increase in yield from applied K than a similar decrease in the higher range of test values. Except for being inverted, this curve is similar to the growth response curve in Figure 3. In fact, these data for yield increases could be converted to actual or relative yields and plotted against soil test values, and a curve very similar to Figure 3 would result.

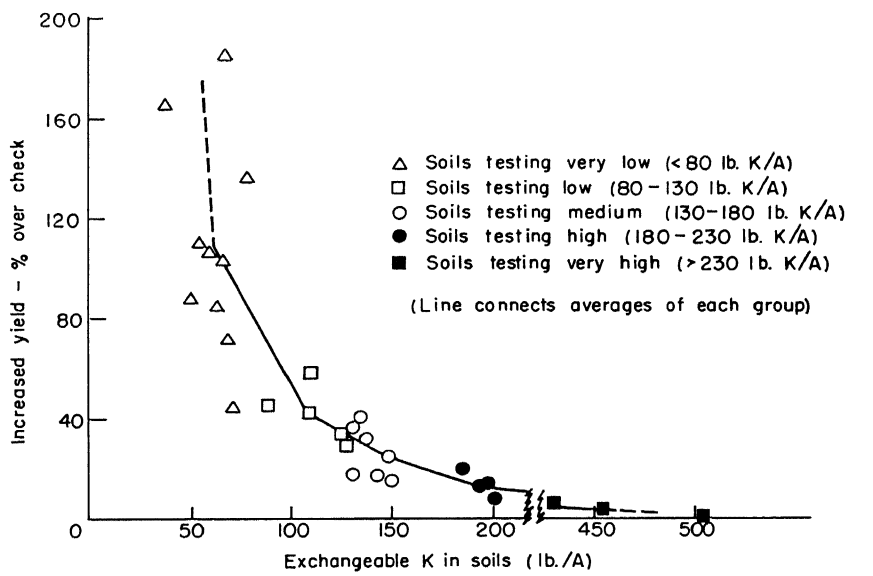

Figure 2. Increases in yields of crops over check treatment when K was applied to soils with various levels of exchangeable K. (K applied at the rate of 35 lb./A/cutting).

TABLE 3.—The relationship of exchangeable potassium as shown by soil test to response of alfalfa (9 cuttings) expressed as percentage of increased yield over check when potassium was applied at 35 lb/A/cutting

Soil Test Range lb K/A			Soil	Exchangeable K lb K/A	Crop Response Inc. in Yield %
Very Low	80	1.	Wooster silt loam	37	165
		2.	Wooster silt loam pH 7.5	50	88
		3.	Clermont silt loam	55	110
		4.	Wooster silt loam pH 7	58	107
		5.	Wooster silt loam pH 6	62	85
		6.	Wooster silt loam pH 7	67	185
		7.	Mahoning silt loam	68	72
		8.	Wooster silt loam	69	44
		9.	Wooster silt loam pH 6	78	136
			Average	63	103
Low	80–130	1.	Mahoning silt loam	88	45
		2.	Clermont silt loam	109	58
		3.	Wooster silt loam pH 7	125	34
		4.	Wooster silt loam pH 6	127	29
			Average	112	42
Medium	130–180	1.	Crosby silt loam	131	37
		2.	Crosby silt loam	131	18
		3.	Wooster silt loam pH 7.5	134	41
		4.	Mahoning silt loam	137	32
		5.	Newton sand	143	17
		6.	Clermont silt loam	150	15
			Average	147	27
High	180–230	1.	Crosby silt loam	185	20
		2.	Rossmoyne silt loam	198	14
		3.	Brookston silty clay loam	201	7
			Average	195	14
Very High	230	1.	Hoytville silty clay loam	405	6
		2.	Toledo silty clay	505	0
			Average	455	3

Linear correlation coefficient, r between exchangeable K and crop responses is 0.61 which is highly significant for the 24 soils included in the calculations. Since the relationship obviously is not linear (Fig. 2), the correlation coefficient for the curvilinear function: exchangeable K vs. logarithm of percentage increase in yield, was computed. Its value was 0.89, which is significantly higher than the linear correlation.

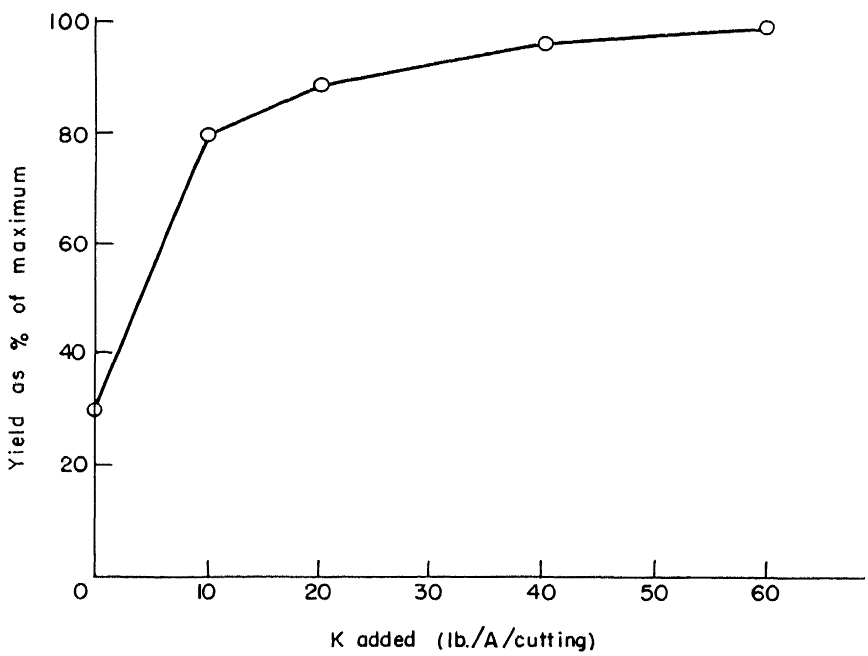

Figure 3. Average yields of alfalfa expressed as percent of the maximum for various rates of K added to several Ohio soils.

Work elsewhere[4] has indicated that there is a high correlation between soil test results for exchangeable K and crop response in the greenhouse. Due to various uncontrolled factors in field soils, one would not expect such high correlation between soil test value and crop response in the field. This point will be further considered in section I.

D. Applied K as a source of available K to plants.

1. **Increasing rates of K as they affect relative yields.** Results were obtained on eight Ohio soils which responded to applied K and which had various rates of K applied for comparison. The relative yields (expressed as percentage of the maximum yield obtained at the highest level of applied K) of alfalfa for the various rates of applied K are presented in Table 4 and plotted in Figure 3.

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[4]Unpublished report North Central Regional Technical Committee #16 on Nutrient Deficiencies.

TABLE 4.—Relative yields of alfalfa (9 cuttings) in the greenhouse at various rates of application of potassium to several Ohio soils

Treatment K/cutting	No. of soils in test*	Yield as % of maximum
lb/A		
0	6	36
10	5	80
20	8	89
40	6	97
60	6	100

*Only soils which showed a yield response to applied K are included here. The same eight soils were compared throughout the study, but not all of them had all rates of treatment, hence the number averaged at each rate differs accordingly.

These results indicate the applied K was available to plants, and accordingly they responded in yields to the added K. A curve such as that in Figure 3 is a typical growth curve. The first increment of 10 lb. of K which was added caused a much greater relative yield increase than the last 20 lb. of K added. In fact, each succeeding 10-lb increment produced less yield increase per pound of K than the previous increment. This type of response to applied nutrient is typical of plant response to increasing rates of fertility supplied. Yet it may not always be easily seen because so often too few data are available for examination.

2. **Increasing rates of K as they affect yields and K contents of alfalfa grown in Ohio soils.** The yields and K contents of alfalfa at various rates of applied K are tabulated in Table 5. Yields on all soils except the Toledo were increased with greater increments of K. On the Crosby, where the K release value was 564 lb/A, the yield was increased nearly 60% by the highest rate of K applied. There were no soils included in this study with K release values in the range 564 lb/A for the Crosby to nearly 2000 lb/A for the Toledo (see Table 1). However, data from the experiment with Sudan grass reported in Table 10, suggest that crops on neither Hoytville nor Brookston, with 1560 and 874/A of K release, respectively, responded consistently in yields to K applied. Nevertheless, they did show consistent increases in K content of the crops with K applied to the Brookston soil. Thus the results on Ohio soils suggest a threshold value for K release of about 700-800 lb/A. Below this value yield response to applied K would be expected

TABLE 5.—Effect of rate of potassium application on yields and potassium contents of alfalfa (9 cuttings) and the resulting potassium status of nine Ohio soils

K Treat-ment	Alfalfa		Soils			
			Exchangeable K		K Released*	
	Yield Ton/A	K Content lb/A	Start lb/A	Finish lb/A	lb/A	% of K Content†
			Wooster silt loam—pH 6—Experiment 1‡			
0	3.9	53	59	32	26	49
180	9.1	204	92	82	14	7
360	10.0	279	72	92	—61	—22
540	10.4	281	77	224	—112	—40
			Wooster silt loam—pH 7—Experiment 1			
0	3.7	49	52	23	20	41
180	10.6	228	71	60	37	16
360	13.8	326	59	77	—16	—5
540	13.3	329	71	166	—116	—35
			Wooster silt loam—pH 7.5—Experiment 1			
0	2.0	27	58	10	—19	—70
180	10.3	217	67	53	—21	—10
360	12.7	303	63	71	—49	—16
540	12.8	336	63	157	—110	—33
			Clermont silt loam—pH 7—Experiment 1			
0	2.2	29	55	11	—15	—52
90	8.8	159	70	16	15	9
180	11.8	217	69	40	8	4
360	12.4	318	80	75	—47	—15
540	13.7	353	71	132	—126	—36
			Mahoning silt loam—pH 7—Experiment 1			
0	6.8	105	61	37	81	77
90	10.6	190	66	55	89	47
180	12.5	258	74	63	67	26
360	13.1	305	75	85	—45	—15
540	12.7	328	58	143	—127	—39
			Crosby silt loam—pH 7—Experiment 1			
0	12.5	178	110	64	132	74
90	14.9	267	135	77	119	45
180	18.1	349	133	83	119	34
360	19.1	449	141	101	49	11
540	19.6	493	117	114	—60	—12

TABLE 5.—Effect of rate of potassium application on yields and potassium contents of alfalfa (9 cuttings) and the resulting potassium status of nine Ohio soils—Continued

K Treatment	Alfalfa		Soils			
			Exchangeable K		K Released*	
	Yield Ton/A	K Content lb/A	Start lb/A	Finish lb/A	lb/A	% of K Content†
			Newton sand—Experiment 2‡			
0	7.2	159	143	109	125	79
90	7.6	199	143	111	77	39
180	7.8	238	143	120	35	15
270	8.5	292	143	128	7	2
			Wooster silt loam—Experiment 2			
0	8.7	129	68	39	100	78
90	10.2	200	68	44	84	42
180	11.5	246	68	43	41	17
270	12.7	324	68	50	36	11
			Toledo silty clay—Experiment 2			
0	16.6	719	503	339	555	77
90	16.1	780	503	350	537	69
180	15.5	756	503	356	429	57
270	16.6	844	503	354	425	50

*This is K released from nonexchangeable form by cropping. Negative values indicate potassium was not released but was fixed in the soil in nonexchangeable form, i.e. was not accounted for in crop or in exchangeable form in the soil.

†These are the percentages that the amounts of K released are of the total K contained in the crops.

‡The soils in Experiments 1 and 2 were cropped at different times and thus under slightly different growth conditions; otherwise, the results are comparable. The Wooster soil in Experiment 2 was a composite of the Wooster pH 7 and pH 7.5 soils of Experiment 1 which had been intensively cropped in the greenhouse without K fertilization followed by moist fallow also in the greenhouse for several months prior to this study.

under intensive greenhouse cropping. This range is somewhat higher than the 250 ppm (500 lb/A) reported by Legg and Beacher (1) from results on Arkansas soils using ryegrass and ladino clover. Except for the fine textured, lakebed soils, most Ohio soils have K release values below the above-mentioned threshhold value (3); hence, they would be expected to respond to K under intensive cropping. Under conditions of poor drainage in the field, supplemental K may be required to maintain high yields even on soils very high in K release.

Potassium contents of the crops were increased by the applied K on all soils included in this study (Table 5). It will be noted that K content of the crops was a much more sensitive index of response to K added than was yield. For example, where yield was increased only a small percentage, the K content was frequently increased several fold.

3. **Increasing rates of K as they affect the status of K in these soils.** Where no K was added, there was a general tendency for the alfalfa (9 cuttings) to remove more K than was exchangeable initially (Table 5). Yet these soils still contained appreciable exchangeable K at the end of this period of cropping. Non-exchangeable K was released to supply this difference. The amounts released were roughly proportional to the K released with boiling nitric acid (see Table 1). As more K was added, less K was released. In fact, in all of the first six soils listed in Table 5, i.e. those in experiment-1, K was fixed instead of released at the higher rates of applied K. Had the rates of application for the Wooster and Newton in experiment-2, extended as high as those in experiment-1, it is probable that K would have also been fixed in these soils at the higher rates.

4. **Method of application with single and multiple rates of applied K.** Yields, K contents of the harvested alfalfa, and the resulting K status of the same nine Ohio soils according to whether K was applied after each cutting or every third cutting are summarized in Table 6. Considering all of the soils, there is a remarkable similarity in both yields and K contents of the crops whether the K was applied after each cutting or three times as much after every third cutting. Examination of the data for the individual cuttings (not shown) revealed that the yields and their K contents were more uniform when the application was made after each cutting. In contrast, these values increased considerably following the relatively high rate of application after each third cutting and dropped progressively during the succeeding two crops (cuttings) which preceded the next K application. In view of this fact, it is perhaps surprising that the resulting averages would be so similar (Table 6). When the rate of applied K was varied along with the method of application, there was a case or two where the yields did not duplicate very well, but the K contents were generally quite comparable. These results would seem to indicate that there is little reason to go to the extra work of applying K to each cutting of alfalfa when the same amount of K could be applied once each season without adverse effects. The cyclic effect described above, however, would suggest that undue extension of the interval between applications might not be wise in the field management of alfalfa meadows. No

TABLE 6.—Effects of method and in some cases rate of application of potassium on yields and potassium contents of alfalfa (9 cuttings) and the resulting potassium status of nine Ohio soils

K Treat-ment lb/A	How applied	Alfalfa		Soils			
				Exchangeable K		K Released*	
		Yield Ton/A	K Content lb/A	Start lb/A	Finish lb/A	lb/A	% of K Content†
		Wooster silt loam—pH 6—Experiment 1‡					
0	------	4.5	81	81	123	123	152.0
315	35 lb/cutting	8.4	249	62	130	2	0.8
315	105 lb/3 cuttings	8.2	247	62	129	—1	—0.4
		Wooster silt loam—pH 7—Experiment 1					
0	------	5.6	82	60	124	146	178.0
315	35 lb/cutting	11.5	259	58	120	6	2.3
315	105 lb/3 cuttings	11.4	264	58	125	16	6.1
		Wooster silt loam—pH 7.5—Experiment 1					
0	------	9.6	131	53	99	177	135.0
315	35 lb/cutting	15.8	301	50	113	49	16.3
315	105 lb/3 cuttings	16.0	306	50	114	55	18.0
		Clermont silt loam—pH 7—Experiment 1					
0	------	6.6	97	16	85	166	171.0
315	35 lb/cutting	18.0	372	55	116	118	31.7
315	105 lb/3 cuttings	16.2	355	55	114	99	27.9
		Mahoning silt loam—Experiment 1					
0	------	11.0	176	55	116	215	122.0
315	35 lb/cutting	17.7	443	85	130	173	39.1
315	105 lb/3 cuttings	18.0	424	85	146	170	40.2
		Crosby silt loam—Experiment 1					
0	------	11.7	199	77	148	270	135.0
315	35 lb/cutting	15.7	420	131	174	148	35.2
315	105 lb/3 cuttings	15.7	403	131	180	137	34.0
		Newton sand—Experiment 2‡					
0	------	7.2	159	143	109	125	79.0
90	10 lb/cutting	7.5	198	143	112	77	39.9
90	30 lb/3 cuttings	7.7	199	143	110	76	38.0
180	20 lb/cutting	8.0	246	143	120	43	17.0
180	60 lb/3 cuttings	7.6	230	143	120	27	12.0
270	30 lb/cutting	8.4	297	143	132	16	5.0
270	90 lb/3 cuttings	8.5	286	143	124	—3	—1.0

TABLE 6.—Effects of method and in some cases rate of application of potassium on yields and potassium contents of alfalfa (9 cuttings) and the resulting potassium status of nine Ohio soils—Continued

K Treatment lb/A	How applied	Alfalfa Yield Ton/A	Alfalfa K Content lb/A	Soils Exchangeable K Start lb/A	Soils Exchangeable K Finish lb/A	K Released* lb/A	K Released* % of K Content†
			Wooster silt loam—Experiment 2				
0	------	8.7	129	68	39	100	78.0
90	10 lb/cutting	11.5	207	68	45	94	45.0
90	30 lb/3 cuttings	9.8	193	68	43	78	40.0
180	20 lb/cutting	12.0	249	68	43	44	18.0
180	60 lb/3 cuttings	11.0	243	68	43	38	16.0
270	30 lb/cutting	12.6	333	68	51	46	14.0
270	90 lb/3 cuttings	12.8	315	68	48	25	8.0
			Toledo silty clay—Experiment 2				
0	------	16.6	719	503	339	555	77.0
90	10 lb/cutting	16.0	781	503	352	540	69.0
90	30 lb/3 cuttings	16.2	777	503	348	532	68.0
180	20 lb/cutting	17.1	749	503	352	418	56.0
180	60 lb/3 cuttings	13.9	762	503	359	438	58.0
270	30 lb/cutting	16.8	854	503	356	437	52.0
270	90 lb/3 cuttings	16.3	833	503	352	412	49.0

*, †, ‡—See footnotes Table 5.

doubt subsoil feeding of the alfalfa would modify the extrapolation from greenhouse to field conditions. This point is considered further in section I.

E. **If exchangeable K is removed by leaching, non-exchangeable K becomes exchangeable.** The results summarized in Table 7 illustrate the fact that when the soil is extracted of its exchangeable K by leaching with ammonium acetate, then allowed to stand; more K becomes exchangeable. At the end of only two days after the first (0 days) leaching, almost 100 pounds of K per acre were extracted from each of the three soils. With further leaching and after greater intervals of time, the amounts removed became more nearly proportional to the K released with boiling, normal nitric acid.

TABLE 7.—The effect of time and repetition of extraction on the amounts of exchangeable K removed with neutral normal ammonium acetate from three soils

Soil*	Exchangeable K in lb/A when extracted after various periods—days								
	0	2	7	14	21	28	35	49	K released†
Hoytville (1442)	446	96	80	115	38	33	45	109	516
Canfield (550)	410	94	64	78	14	17	24	20	311
Clermont (168)	104	98	44	60	10	15	14	15	256

*The amounts of K released by boiling 1N HNO_3 are shown in parenthesis beside the soil series names.

†K released by repeated leaching, i e. total removed minus that obtained by the first leaching.

From these data (Table 7) one can safely conclude that the exchangeable K could hardly be brought to zero level by leaching or by cropping as long as any reserve K is present. Therefore, a soil test for exchangeable K is not an absolute measure of K available to crops over an extended period of time. It is a **relative** index of the amount of K available to crops. It might be compared to the air pressure in a tire. Comparison of the pressure in a tractor tire with that in an automobile tire might reveal they were the same. Yet, due to its size, more air would be present in the tractor tire. Similarly, the soil test for exchangeable K initially (0 days) was practically the same for the Hoytville as for the Canfield (Table 7), yet the amount ultimately removed by leaching of the Hoytville greatly exceeded that from the Canfield. If the air is permitted to escape through a gauge from both the tractor and automobile tires, frequent testing would reveal that the rate of change in pressure varies with the size of tire. Once this rate of change in pressure is known, it is possible to predict more accurately the amount of air which remains in the different types of tire. Likewise, as the repeated leaching demonstrates, frequent testing of the different soils so that the rate of change in exchangeable K with cropping can be determined, a more reliable estimate of the amount of K ultimately obtainable by crops can be made. This is perhaps just another way of stating that since the exchangeable K is modified by the amount of K released from non-exchangeable form, both must obviously be taken into account if accurate K recommendations are to be made on soils intensively cropped over extended periods.

Incidentally, this was a highly fertilized Canfield soil used in this study; otherwise, the first four leachings would have yielded much less K (Table 7). Since this soil released more K with boiling HNO_3 than that expected (3), this is more evidence that K fixed by drying the soil in preparation for testing was released by HNO_3, and was also obtained by repeated leaching with ammonium acetate.

F. **If available K is removed by cropping, non-exchangeable K becomes available.** The soils previously treated, cropped, and reported in Table 5 were recropped without further K treatment. The yields and K contents of the crops are contained in Table 8. It is evident that the alfalfa obtained more K from most of these soils than was exchangeable at the beginning of the cropping period (see exchangeable K finish, Table 5). The additional K required to supply the needs of the crops and to maintain a level of exchangeable K necessarily came from non-exchangeable K. Thus K applied and not used by one crops is largely recoverable by the next, even though the soil test for exchangeable K doesn't always reveal its presence.

G. **Relative availability of fixed K and KCl to plants.** In section B above (data in Table 2), it was pointed out that K fixed by drying was released with boiling HNO_3 and thus might be available to plants. The results assembled in Table 9 are from one of the three soils included in a study and published elsewhere (2). The K-soil used as a K fertilizer to more of the same otherwise untreated soil was adjusted so that the amount of exchangeable K equaled the amount of K applied as KCl in a comparable treatment. The fixed K in the K-soil treatment was present in addition to the exchangable K. With the exception of the extremely low rate of applied K where differences are probably not significant, the K-soil supplied more available K than the comparable KCl treatment. In fact, even though only one level of total K for each source is available for comparison, it appears that the total K offered to the plant in the K-soil and KCl treatments are similar in the amounts of K available to the alfalfa. This could only be true when the fixed K is substantially available to plants. The other two silt loam soils studied also showed this general trend (2). Soils of different textures are currently under study in the greenhouse.

Since K fixed in moist soils is largely not recovered with boiling HNO_3, it does not seem likely that this form of fixed K would be available to plants. Undoubtedly there was some K fixed in the moist soil from the KCl added directly to the soil, but this quantity may not have been greatly different from that fixed in the initial preparation of the

TABLE 8.—Effect of previous applications (residual effects) of K on yields and K contents of alfalfa (9 cuttings) grown in nine Ohio soils*

Previous K Treatment lb/A	Alfalfa Yield T/A	Alfalfa K Content lb/A
Wooster silt loam—pH 6		
90	----	----
180	4.5	81
360	4.5	102
540	6.6	205
Wooster silt loam—pH 7		
90	----	----
180	5.8	82
360	6.9	110
540	9.6	188
Wooster silt loam—pH 7.5		
90	----	----
180	9.6	131
360	11.9	181
540	11.6	207
Mahoning silt loam—pH 7		
90	11.1	176
180	12.3	202
360	11.7	200
540	15.2	295
Crosby silt loam—pH 7		
90	11.7	199
180	14.4	238
360	14.2	267
540	14.9	292
Clermont silt loam—pH 7		
90	6.6	97
180	8.3	121
360	9.7	159
540	10.6	196

TABLE 8.—Effect of previous applications (residual effects) of K on yields and K contents of alfalfa (9 cuttings) grown in nine Ohio soils*—Continued

Previous K Treatment lb/A	Alfalfa	
	Yield T/A	K Content lb/A
	Wooster silt loam†	
0	5.7	57
90	5.9	71
180	6.7	74
270	6.8	80
	Toledo silty clay†	
0	12.2	340
90	11.9	350
180	12.2	370
270	13.1	400
	Newton sand†	
0	4.8	70
90	4.7	73
180	5.5	91
270	5.7	105

*These are the same soils as those shown in Table 5.

†Analysis of these soils before and after cropping indicated relatively constant amounts of K released from non-exchangeable form for a given soil regardless of previous treatment. Roughly one-half of the K in the plants was released from non-exchangeable form (the remainder from exchangeable form) in the Toledo; two-thirds was released from this form in the Newton; and nine-tenths was similarly released in the Wooster.

K-soil. No effort was made to evaluate the availability of moist fixed K. However, it presumably would have been present perhaps in similar amounts of both K-soil and KCl treatments.

H. **Effect of other fertility additions to soils on response of plants to K.** In all of the previous studies reported herein no attempt was made to evaluate the importance of other fertility on the response of plants to K. What was considered to be adequate quantities of nitrogen and phosphorus were supplied to the plants while the response to K was determined. The present study was designed to determine the importance of N, P, and lime on crop response to applied K. The soils

TABLE 9.—Yields and K removed in nine cuttings of alfalfa grown in Wooster soil treated with a portion of the same soil containing additional exchangeable and fixed K and with comparable amounts of K added as KCl

Source*	Treatment—K added			Alfalfa	
	Exch. K (or KCl) lb/A	Fixed K† lb/A	Total K lb/A	Yield T/A	K in Crops lb/A
K-soil	10	12	22	13.1	146.6
KCl	10	0	10	12.8	150.0
K soil	70	88	158	15.9	236.0
KCl	70	0	70	13.8	178.5
K soil	130	164	294	17.9	359.0
KCl	130	0	130	14.4	218.0

*K was added to a portion of this soil as KCl at the rate of 1000 lb/A. The soil was then wet and dried for about 10 consecutive cycles so as to fix a large portion of the K added. Then the resulting K-soil was added as supplemental K to the untreated portion of the soil in sufficient quantities to give the rates shown above.

†Fixed K is K fixed prior to the plant study. It is that added to the treated portion of soil but not accounted for as water soluble or exchangeable. It would include both moist and dry fixed K in the K-soil. Undoubtedly there was some K fixed in the moist soil from the KCl added both directly and indirectly to the soil, and probably some of the additional exchangeable K in the treated soil was fixed by the untreated portion when placed with it. But no attempt was made to determine these quantities.

chosen were the Clermont, Rossmoyne, Brookston, and Hoytville representing a range in K released with HNO_3 from 207 to 1560 lb/A. However, each of the soils had somewhat higher than normal exchangeable K contents due to previous fertilization. The results obtained with sudan grass as the test crop are summarized in Table 10. There was much less variation in K content of crops due to treatment on unlimed than on limed soils. As in previous studies, K contents were more sensitive than yields as a measure of response to K. In this study phosphorus additions had little to no effect on K content of crops and generally very little effect on yields. Only one level of added P was included.

In contrast to P, extra nitrogen had marked effects on the crops both directly and indirectly. Some nitrogen (150 lb. of N per 2,000,000 lb. of soil) was required in all treatments to maintain satisfactory growth. Extra nitrogen (300 lb/A) increased the yields of crops on all soils with the greatest increase on Hoytville. In fact, crops on this soil responded only to extra N in yields and total K content. Similarly, extra N decreased the percentage of K in all crops, except the Hoytville. Crops on these soils i.e. Clermont, Rossmoyne, and Brookston increased systematically in % K and total K as increased rates of K were applied at both low and high N levels. This suggests that K was regulating the rate of growth in all soils except the Hoytville. In the latter case, sufficient K was being released so that some other factor than K (chemical or physical) was probably limiting the growth of the plants.

Extra nitrogen generally increased the uptake of K by crops. However, the unlimed Clermont and Rossmoyne and the Brookston at the high K rate were exceptions to the rule. Additional K generally increased both yields and their K contents only when additional N had been applied.

I. **Response of alfalfa in the field to applied K.** Increasing rates of K were applied to an established stand of alfalfa at Wooster. Average yields and percentages of K in crops were determined and are summarized in Table 11. The data point out that even where yields were not affected, the percentage of K in the hay reflected the treatments very well. It should be noted that this soil had been fertilized quite well prior to these treatments as indicated by the 185 lb. of K/A initially present as exchangeable K. Since this value had dropped by the end of the second cropping season to values below 100 lb/A in all cases except at the two highest rates of application, it is probable that crops on this soil would soon begin to respond with increased yields to the K applied. It could be that the deep rooted alfalfa was obtaining enough K from the subsoil to supply the needs for maintaining yields, even though the K content showed the effects of the treatment. Shallow rooted crops, including alfalfa during establishment, would be confined to the topsoil. In such cases, the response of the crop to applied K on a soil where exchangeable K in the topsoil had declined to this level would be expected. Similarly, established alfalfa would likely respond differently than it did if there were no other K available. It should be remembered that the exchangeable K values in Table 11 are following the two-year cropping period. So, even at the beginning of the second cropping season, the exchangeable K values were considerably higher than those in the table.

These results (Table 11) illustrate another point. If no K were added to established alfalfa stands simply because yields were not increased, and if the explanation for the lack of response is the subsoil contributing the necessary extra K; then the topsoil would become

TABLE 10.—Total yields, average percentage K, and K content of six cuttings of sudan grass grown in four Ohio soils with various treatments

Treatment lb/A	Yield T/A	% K	K Content lb/A
N P_2O_5 K		Clermont silt loam	
Limed			
150 + 0 + 0	7.3	1.14	167
150 + 0 + 80	7.4	1.50	221
150 + 105 + 0	7.6	1.11	169
150 + 105 + 80	7.9	1.44	226
150 + 105 + 160	8 1	1.70	275
300 + 105 + 0	9.4	0.98	185
300 + 105 + 80	10.1	1.20	242
300 + 105 + 160	10.9	1.44	313
Unlimed			
150 + 0 + 80	6.8	1.56	213
150 + 105 + 80	6.7	1.57	209
150 + 105 + 160	8.2	1.69	276
300 + 105 + 80	9.1	1.32	239
300 + 105 + 160	8.8	1.60	282
N P_2O_5 K		Rossmoyne silt loam	
Limed			
150 + 0 + 0	8.2	1.53	270
150 + 0 + 80	8.6	1.77	306
150 + 105 + 0	8.6	1.45	251
150 + 105 + 80	8.7	1.76	306
150 + 105 + 160	8.4	2.08	349
300 + 105 + 0	10.0	1.27	253
300 + 105 + 80	11.0	1.56	343
300 + 105 + 160	11.3	1.87	422
Unlimed			
150 + 0 + 80	7.8	2.01	314
150 + 105 + 80	8.1	1.88	305
150 + 105 + 160	8.0	2.10	338
300 + 105 + 80	10.9	1.52	332
300 + 105 + 160	11.2	1.73	338

TABLE 10.—Total yields, average percentage K, and K content of six cuttings of sudan grass grown in four Ohio soils with various treatments—Continued

Treatment lb/A	Yield T/A	% K	K Content lb/A
N P_2O_5 K	Brookston silty clay loam		
Limed			
150 + 0 + 0	8.6	1.87	323
150 + 0 + 80	8.8	2.03	356
150 + 105 + 0	8.5	1.79	305
150 + 105 + 80	9.5	1.95	370
150 + 105 + 160	9.5	2.13	404
300 + 105 + 0	12.2	1.50	367
300 + 105 + 80	11.9	1.71	408
300 + 105 + 160	11.8	1.73	409
N P_2O_5 K	Hoytville silty clay loam		
Limed			
150 + 0 + 0	10.1	2.54	515
150 + 0 + 80	9.8	2.43	478
150 + 105 + 0	10.0	2.56	510
150 + 105 + 80	9.7	2.55	493
150 + 105 + 160	9.6	2.52	484
300 + 105 + 0	14.6	2.46	717
300 + 105 + 80	13.1	2.56	670
300 + 105 + 160	14.0	2.63	739

depleted to a point where it would be far too low to supply the K requirement of the crop which follows. Too much applied K would no doubt be uneconomical because of lack of yield response and luxury consumption of K by the crop i.e. more K might be taken up than is necessary or even good for the crop. But a maintenance application of K would seem wise even when immediate yield increases were not obtained.

TABLE 11.—Yields and potassium content of alfalfa grown in the field under different levels of potassium fertilization and the resulting effects on the potassium status of the soil (Wooster)

Treatment	Yields 3 cuttings/year		Potassium 3 cuttings/year		1954-1955 Period*		
	1954	1955	1954	1955	Total K in crops	K Balance in soil†	Exch. K‡
	T/A	T/A	%	%	lb/A	lb/A	lb/A
0	3 44	5.60	1.10	1.10	198	—106	91
30	3 33	5 44	1.11	1.07	192	—73	89
60	3 14	5.36	1.18	1.10	196	—44	92
90	3.30	5.59	1.21	1.20	211	—27	95
120	3.19	5.54	1.20	1.25	212	0	93
180	3.35	5.68	1.30	1.27	224	+52	96
240	3.36	5.56	1.42	1.37	244	+100	105
360	3.26	5.66	1.63	1.55	290	+198	129

*All data here are based on three of the six replications of the experiment.

†Computed as follows: (K in crops minus K applied minus decrease in exchangeable K).

‡Exchangeable K in the topsoil at the end of the two year cropping period; exchangeable K at the beginning of the experiment was approximately 185 lb/A varying slightly on different plots.

SUMMARY

Thirteen Ohio soils, varying from 49 to 496 pounds of exchangeable K per acre and from 190 to 1968 pounds of K released per acre with boiling HNO_3, were studied in the greenhouse and laboratory.

Results were briefly summarized as follows:

1. Addition of K to moist soils and analysis after equalibration revealed a certain fraction was exchangeable and another was fixed in non-exchangeable form. Drying in the oven at 105° C. for at least 24 hours fixed still more of that previously exchangeable. The moist fixed K was not to any great extent extractable with boiling 1N HNO_3, while the dry fixed K was largely extractable with the HNO_3.
2. A highly significant correlation was found between the exchangeable K and the response of alfalfa to applied K.

3. The relative yields of alfalfa at various rates of K applied indicated the added K was available, and the resulting curve of yield versus amount of K added was the typical growth curve i.e. decreasing rate of yield increase per additional unit of K applied.

4. Crops on only those soils with K release values above a range of about 700-800 lb/A failed to respond with increased yields as K was applied at increasing rates in greenhouse studies. Except for the fine textured, lakebed soils, most Ohio soils have K release values below this range; hence, they would be expected to respond to K fertilization under intensive cropping. Under adverse field conditions, any soil may require additional K to sustain maximum yields.

5. More K was taken up by nine cuttings of alfalfa than was initially exchangeable; yet there was still exchangeable K after cropping. Non-exchangeable K necessarily was released to make up this difference, and the amounts released were roughly proportional to K released with boiling HNO_3. When sufficient K was added, K was fixed instead of released.

6. Average yields and K contents of alfalfa were remarkably similar whether K was applied after each cutting or three times as much after every third cutting. However, there was a tendency for yields and K contents of crops to increase markedly after the less frequent-higher rate treatment followed by progressive decline until the next treatment. This suggested that for a given total amount of K applied over a period of time, it may not be advisable to unduely extend the interval between K applications when dealing with field fertilization of meadows.

7. Removal of the exchangeable K by repeated leaching with ammonium acetate as well as by cropping resulted in additional K becoming exchangeable. Therefore, exchangeable K can only be a relative measure of total K available to crops, since it would be supplemented by the amount the soil is able to release from non-exchangeable form. It is evident that this K release value for a given soil must be taken into account in making accurate recommendations for K fertilization based on soil tests.