

yielded rather large amounts of nitrate over a long period of time in both soils (Figures 2 and 3).

COMPARISONS FOR BARLEY PRODUCTION. The same nitrogen fertilizers were applied at a rate of 50 pounds of N per acre to Laveen clay loam and Superstition sand to evaluate them as sources of nitrogen fertilizer for barley grain production. The nitrogenous materials increased grain yields significantly above that of unfertilized plots except for dicyanodiamid and guanidylurea sulfate (Table I). Thiourea appeared significantly better than the other sources on both soils. A second crop of barley planted to the same plots on both soils demonstrated a distinct residual effect due to the previous year's application of thiourea. The other nitrogen sources failed to show residual effects for a second barley crop. Thiourea has an inhibitory effect on the rate of biological nitrification, thus slowing down nitrogen loss through reactions characteristic of nitrate or nitrite (18).

Ammonium sulfate was found to support significantly higher winter barley yields than calcium nitrate when compared in Yuma, Arizona, on Superstition sand, according to Stanberry (34). This is in agreement with the nitrification data which show that ammonium sulfate maintained a higher level of nitrogen in this calcareous soil over a period of a year than did calcium nitrate.

Enigma of Soil Nitrogen Balance Sheets

The failure of nitrogen balance sheets to balance soil nitrogen gains and losses constitutes an enigma that continues to resist complete solution.

In 1954, Allison (3) discussed "the enigma of soil nitrogen balance sheets" in detail. Little has transpired during the

last 8 years to change the situation. Also, after balance sheets are made for calcareous soils, income and outgo do not completely balance even though apparent account has been made of all known soil-nitrogen gains and losses. Thus calcareous soils do not differ from neutral and acid soils in the enigma.

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Movement of Applied Potassium in Soils

MOVEMENT or mobility of potassium (K) in soils, as well as movement of other elements essential to plant growth, has been a subject of much investigation, particularly during the past three decades. After gaining some understanding of soil K and its distribution in soil profiles, information was needed as to the fate of K applied as crop residues, manures and chemical fertilizers. Van Alstine (69) prepared an early review that included some in-

formation on movement of K, but data at that time were limited. Many experiments involving additions of materials to soils and subsequent leaching with applied water or rainfall have been conducted since that time. Potassium determinations have been made on the leachate percolating through the soil and/or on various depth increments of the soil profile.

While exchangeable K has been the fraction usually determined, nonex-

changeable K has also been studied. Experiments have been conducted in laboratory, greenhouse and field lysimeters of various types (28) and in field trials with various treatments.

Needless to say, the literature on K movement in soils and factors affecting it is voluminous, but space does not permit coverage of all material which could be appropriately cited. The objectives in this review are to discuss the factors influencing movement of

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The gross movement of K in soils and factors contributing to movement are reviewed. Data from lysimeters as well as field profile sampling studies are presented. Practical implications of results are discussed. Practices for reducing K losses on soils where a leaching problem exists are suggested. Where adequate safeguards are used in management of sandy soils, annual losses of K applied at recommended rates are very low, possibly from 5 to 20 pounds of K per acre. Losses from fine sands may range from 5 to 15 pounds per acre under medium and relative high rates of K fertilization (200 to 400 pounds of K per acre). However, on silt loam and finer textured soils of the Midwest and West, leaching of K will be practically nil. High yields, particularly of some crops, remove large amounts of K. Hence, except with very high rates of K, there is little possibility of loss. Where moderately high rates of K are applied, high recovery and residual crop response further attest to low losses of K.

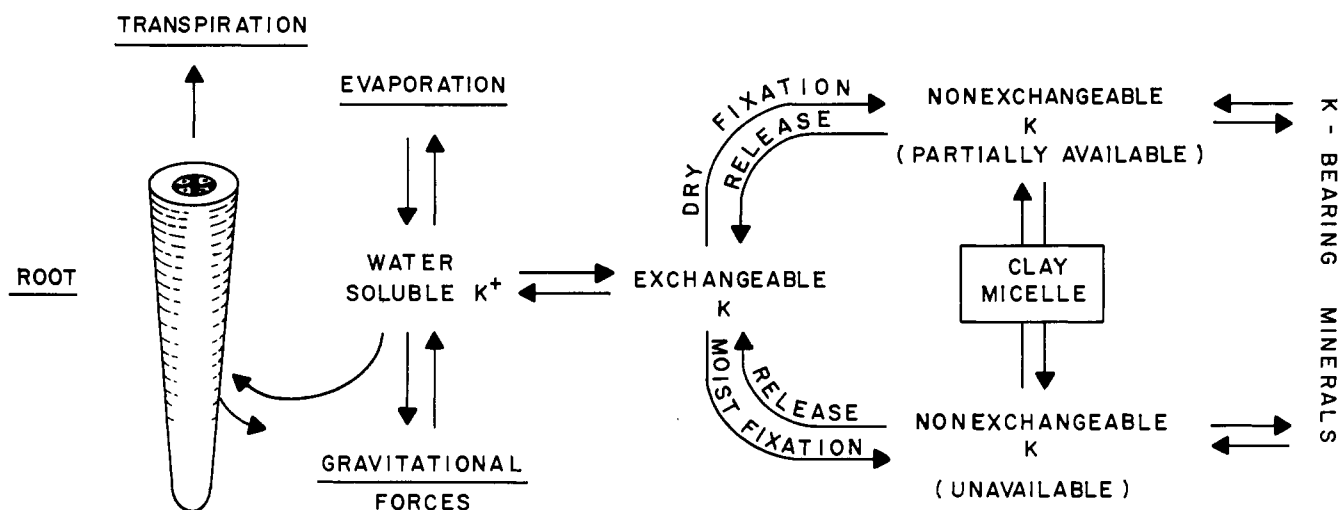


Figure 1. Diagram of K equilibria and some of the forces acting upon water-soluble K

applied K and to present results obtained by various workers that are applicable to understanding gross movement of K from the rooting zone of crops. Those interested in micro K movement in soils are referred to the work of Barber (3), Kemper (26), and Letey and Klute (37).

Factors Influencing Movement of Potassium

A schematic K equilibria diagram, adapted from a diagram by McLean and Simon (43), indicates some of the forces influencing applied K (Figure 1). As soluble K moves into the soil solution by diffusion or with the soil water, it comes under the influence of the soil environment. The latter can drastically alter the rate of K movement. Some of the factors acting on soluble K and results produced are discussed below.

Cation Exchange Capacity (CEC). The capacity of a soil to retain applied K will depend to a large degree on its CEC. The organic matter and clay fractions are primarily responsible for CEC, and act to retard K movement. For an increase in K on the exchange

complex, there must be an equivalent decrease in another positively charged element or elements, in order for the negative charges of the exchange complex to remain in balance.

ORGANIC MATTER. Organic matter has a marked influence on the CEC of soil and the content of mineral soils may range from 0.1 to 5% or more. Jones (24) reported that the organic fraction may account for 30 to 60% of the exchange capacity of many soils. Study of Coastal Plain soils (25) indicated that an average of 55% of the CEC of these soils was due to organic matter. Spencer (62) worked with several fine sand soils in which organic matter accounted for 80% of the CEC.

In the research by Jones (24), organic matter extracted from Carrington silt loam had an exchange capacity of 528 meq./100 grams, while for the soils used by Kamprath and Welch (25), CEC of organic matter ranged from 62 to 279 meq./100 grams. The latter indicated that about 20% of the hydrogen associated with organic matter is strongly ionized. This would influence ability to retain K.

SOIL TEXTURE. The textural class or proportion of soil separates (sand,

silt, and clay fractions) making up a soil will influence CEC, water holding capacity, and rate of water movement, all of which affect K movement. The fine silt fraction can contribute exchange sites (45), but clays usually have the greatest capacity. In general, the greater the per cent clay, the higher the exchange capacity and moisture holding capacity, both of which interact to retard K movement.

Due to soil developmental processes the per cent clay usually increases with soil depth, producing a zone of maximum accumulation (B Horizon) which may impede water and hence K movement.

TYPE OF CLAY MINERALS. Weathering of soils causes the formation and/or disintegration of clays. Soils usually contain a mixture of clay minerals, each type having different properties and capacities to retain K and other cations. Clays of the kaolinitic group have the lowest CEC (< 10 meq./100 grams). The CEC of the illitic or hydrous mica group is intermediate (35 to 50 meq./100 grams), while the montmorillonitic group is relatively high (80 to 120 meq./100 grams). Indications are that as weathering pro-

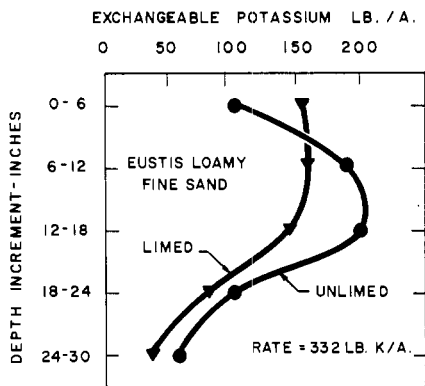


Figure 2. Influence of lime on reducing movement of K applied at 332 pounds of K per acre as muriate of potash (Eustis loamy fine sand)

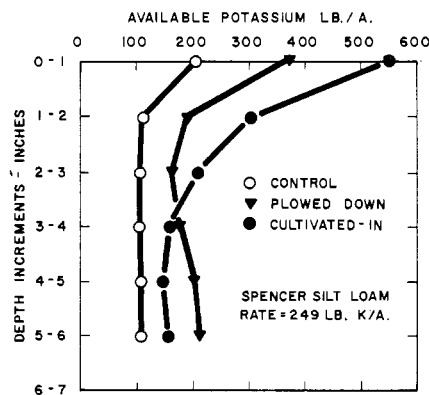


Figure 3. Available K in unfertilized and fertilized Spencer silt loam soil 2 years after plow-down and cultivated-in K applications

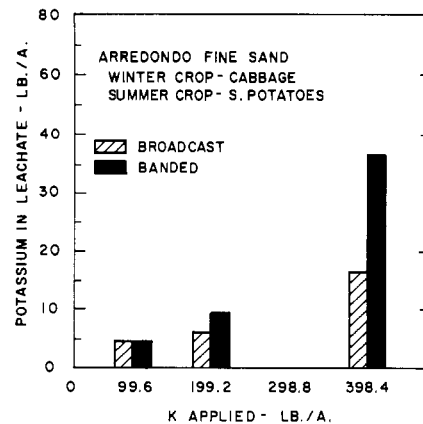


Figure 4. Potassium in lysimeter leachate with various rates of K broadcast and banded in Arredondo fine sand (rainfall = 62.4 inches)

gresses, there is a tendency toward the formation of clays having lower exchange capacity. Vermiculitic clays have striking capacity to bond added K in nonexchangeable form, or at least in a form that is slowly released.

Considerable evidence exists from evaluation of K equilibria reactions that much of the K that is initially "fixed" will again be released (Figure 1). Magistad (42) suggested the equilibria relations that have subsequently been observed among the various forms of soil K. Comprehensive coverage of fixation and release of K are by Volk (73), DeTurk *et al.* (12), Reitemeier *et al.* (57), Schuffelen and van der Marel (58), and McLean and Simon (43).

Soil Reaction and Liming. Peech and Bradfield (51) reviewed work on the influence of lime applications on soil K. Results were reported to be somewhat confused, but it was suggested that if experimental conditions were properly evaluated results would be reconciled. Evidence indicated that the degree of base saturation and presence of neutral salts would determine to a large degree the influence of lime on increasing or decreasing concentrations of K in the soil solution. These authors also indicated that liming an acid soil lacking neutral salts would release K to the soil solution.

That the latter is true on sandy soils may be inferred by the results of Gammon (17). He reported a reduction of 36 p.p.m. in exchangeable K on a Leon fine sand (pH 4.7) one year after application of 2.7 tons of lime per acre (pH 6.0). MacIntire (38), using shallow lysimeters, found that applications of CaCO_3 tended to reduce annual loss of soil K. In many instances, data of the original papers have been recalculated and expressed in different units to aid in the uniformity of this discussion and in making comparisons.

Many have reported that once soils are limed, their capacity to retain K is

often enhanced. Shaw and Robinson (61) reported results of a small fallow lysimeter experiment using CaCO_3 equivalents of three liming materials on an acid Hartsell loam. These authors, as well as MacIntire (38), found the reduction of leached K was in direct relation to the reactivity of the lime used, and that the K loss ratio of unlimed to limed soil was about 2.7:1.

Lutrick (36) observed the influence of lime on decreasing the movement of applied K to lower depths. The K distribution in various depth increments from lime and unlimed treatments which received 332 pounds of K per acre as muriate of potash is plotted in Figure 2. Brown (7) reported that leachability of K in field trials was reduced 50% by liming. MacKay and MacEachern (41) indicate results are dependent on the rate of liming and the time over which the soil is sampled.

MacIntire *et al.* (40) found that calcite and dolomite were effective in increasing K retention early in an experiment, but after the 7th year the effectiveness decreased. Over 80% of the 172 pound annual rate of K was retained during the first 3 years.

Changes have been noted in the CEC of some soils with increases in pH. Nolan and Pritchett (49), using 6-inch laboratory lysimeters, adjusted the pH of two Red Bay loamy fine sands. The soil reactions and CEC are presented in Table I. As acidity was reduced and the pH adjusted toward neutrality, the exchange capacity increased, but at pH 8.1 it was decreased. The leachability of added K was markedly reduced as pH approached neutrality. The authors proposed that the reduction in K loss from liming was due to an easier substitution of K for Ca than for H or Al, which formerly dominated the exchange complex, and an increase in the effective exchange capacity.

Similar results on the influence of increasing pH and base saturation have

Table I. Changes in CEC Produced by Adjusting Soil Reaction

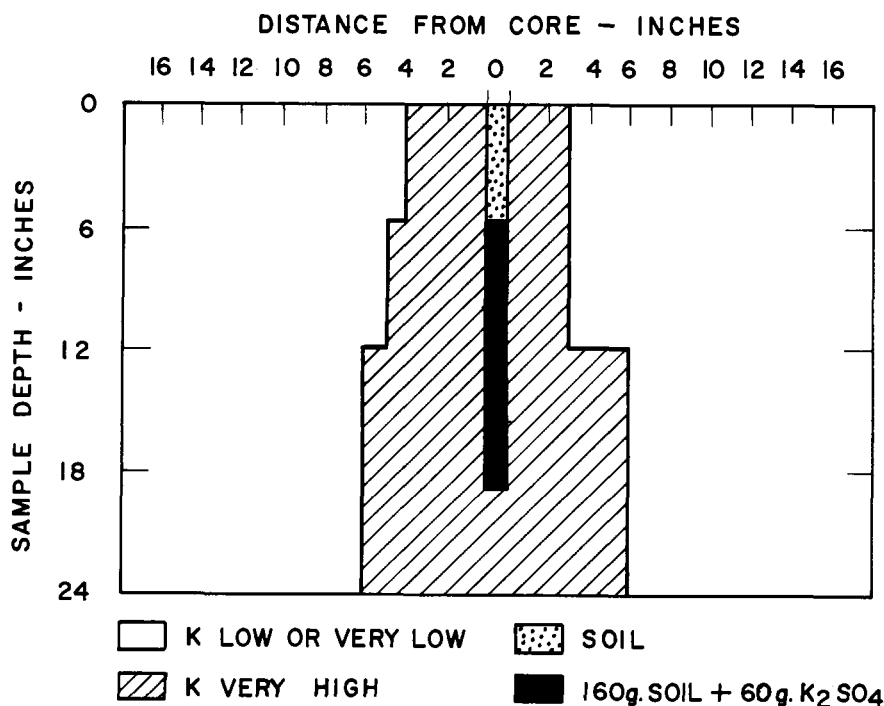
(Red Bay loamy fine sand)

Soil pH	CEC, Meq./100 Grams
4.6	7.07
5.3	8.95
6.7	10.76
8.1	8.78

been reported by others (4, 8, 16, 79). Wicklander (78) discussed the reactions involved in liming and pointed out that the concentration of Al^{+3} in the soil solution becomes low as pH approaches the neutral range, due to the bonding energy changes of Al-hydroxyl complexes and the precipitation of $\text{Al}(\text{OH})_3$. Too, the bonding strength of weak acids (SiOH and OH) become active as pH is increased. Thus, liming should tend to favor adsorption of cations such as K.

Wicklander points out that because of the increased ΔF_H of limed soils, leaching waters should replace cations with greater ease. However, Pratt *et al.* (55) found that limed Al-treated soils released less K than H-soils, and that in the former there was no change in K release with increasing pH. In subsequent studies on 15 soils (53), it was found that a large amount of the CEC was pH dependent.

Method and Rate of Potassium Application. APPLICATION OF BROADCAST K. Movement of applied K can be influenced by method of application. Love *et al.* (34) found a difference between broadcast plow-down and cultivated-in K (Figure 3). For the cultivated-in method of application, it is apparent that there was only slight downward movement of K. The increase in surface K (0 to 1 inch) was attributed to leaching from mature oat plants harvested the previous fall,



RELATIVE POTASSIUM DISTRIBUTION

Figure 5. Distribution of K as shown by K test level 3 years after core application in Wooster silt loam

although evaporation and K release through wetting and drying could have been responsible in part.

BAND AND BROADCAST K. Sears (59), working on calcareous soils in Illinois, studied the effects of hilldropped *vs.* broadcast placement of K on corn yields. On a brown sandy loam soil, corn yields were increased 44 bushels per acre from 39 pounds of K per acre applied hilldropped, but only 16 bushels per acre from 83 pounds of K per acre broadcast. Disregarding positional availability, Sears indicated that the small residual effect of K on these sandy soils, once thought to be due to leaching, was probably due to fixation. On the basis of the data, annual K applications were suggested for such soils.

Volk and Bell (70) used banded (two double concentric bands, 8 inches apart and 3 inches deep) and broadcast (worked into surface 4 inches) placement of 83 pounds of K per acre in 4-foot lysimeters on an uncropped or fallow Norfolk loamy fine sand. Loss of K by leaching was 2.7 times greater from the banded treatment, but still amounted to only 8.8 pounds per acre.

Nolan and Pritchett (56) compared banded and broadcast placement of KCl applied at several rates to an Arredondo fine sand in lysimeters under winter and summer crops. A banded-fallow treatment was not included so their results cannot be directly compared with those obtained by Volk and Bell. However, K losses for the

banded and broadcast rates under the winter crop of cabbage and summer crop of sweet potatoes were selected for comparison, because of the crops included they should show the greatest K loss. For the low rate of application, cumulative K removal for both placements was only about 4.5 pounds per acre. As the rate was increased to nearly 400 pounds of K per acre, the banded treatment lost about 20 pounds of K per acre more than the broadcast treatment (Figure 4). Based on K hydrolysis that probably occurred with higher concentrations of banded K, and the increased exposure of K to exchange sites under broadcast placement, these results are what might have been predicted (64).

SEWAGE EFFLUENT IRRIGATION. Sessing (60) evaluated nutrient applications through irrigation with sewage effluent on a Miami silt loam and a muck soil. Total K applications during a 10-year period of effluent irrigation were nearly 1200 pounds of K per acre. Lysimeter percolate from the Miami silt loam which was cropped to Sudan grass showed an annual loss of 4.5 pounds per acre per year. Annual loss from the muck soil only averaged 3.7 pounds of K.

CORE PLACEMENT AND LATERAL MOVEMENT OF K. Gourley and Wander (18), working with orchards, became concerned about the slowness with which surface applications of K reached absorbing roots. Small holes 18 inches

deep were placed about trees in two concentric rings 9 and 12 feet from the trunks. A mixture of soil and the K-carrier was placed in each hole. K applied in this manner was readily taken up by trees.

Soil tests were used 3 years after application to check on the pattern of K movement. Samples were taken in a grid pattern, each sample being 1 inch wide, 1 inch deep, and 6 inches in vertical length, covering an area 10 by 24 inches on either side of the core. The relative levels of K that could be established using the Thornton quick test were very high, high, medium, low, and very low.

Both lateral and vertical movement of K occurred (Figure 5). Lateral movement appeared to be at least 6 inches on either side of the core treatment. Samples taken from the surface indicated a very high level of K in the soil 3 to 4 inches horizontal from the core even though the K-soil mixture had all been applied below 6 inches. Even greater upward movement occurred with the KCl treatment than with the K₂SO₄ source.

Chemical Source, Particle Size, and Coatings. Even though muriate of potash accounts for well over 90% of the fertilizer K applied in the United States, it is well to evaluate the influence that chemical form, particle size, coatings, and associated fertilizer materials may have on K movement. Review of information on this subject is important because new K carriers may soon be on the market.

CHEMICAL SOURCE. MacIntire *et al.* (39), working with a Hartsell fine sandy loam in shallow (7 inch), filled-in lysimeters, evaluated leaching of K from potassium metaphosphate (KPO₃) and potassium sulfate (K₂SO₄), with and without lime. At the 166-pound per acre K rate, lime markedly reduced K movement from both sources, and more K was leached from the K₂SO₄ than from the KPO₃ source. The difference was greatest on the unlimed soil. The reverse effect, however, was found with 830 pounds of K per acre. Under the heavier rate considerably more K was lost from the KPO₃ source than from the K₂SO₄. Ca and Mg losses were much reduced under the heavy application of KPO₃. It was proposed that this treatment caused precipitation of Ca- and Mg- phosphates which in turn reduced the relative capacity to retain K.

Ayres and Hagihara (2) studied the influence KCl, K₂SO₄, and K₃PO₄ on K retention in several humic and hydrol humic latosols soils in Hawaii. Two 15-inch percolation tubes set in sequence to represent the top 2 feet of soil were used. The base saturation of these soils ranged from 1.3 to 5.5%, while their CEC ranged from 37.6 to

65.0 meq./100 grams. Water was applied in 2.5-inch increments until 90 to 100 inches of percolate were collected. Potassium was applied at the rate of 1038 pounds per acre, on a surface area basis. The order of retention of K from the three sources was $KCl < K_2SO_4 < K_3PO_4$. DeTurk *et al.* (12) had noted that when K was applied as the phosphate, a considerable portion of K became exchangeable because of the affinity for soils when associated with K_3PO_4 .

Ayres and Hagihara (2) studied other K-phosphate sources. Results indicated that K retention from that applied as KPO_3 and K_2PO_4 was similar. Subsequent K retention studies were conducted using combinations of phosphate carriers and KCl. Ammophos, superphosphate, and treble superphosphate were used with KCl and applied in different ratios of P:K. Mixtures of ammophos and KCl materially increased the retention of K over KCl applied alone (1038 pounds of K per acre) to the surface of the soil in a P:K ratio of 1.4:1. As part of the same study, Ayres and Hagihara also found that applications of $(NH_4)_2SO_4$ with KCl resulted in a substantial increase in the retention of K. The increases in K retention were related to increases in exchangeable K.

Regarding the influence of N on loss of K, Gow (19) found that if K was applied 45 days after application of NH_4Cl and monoammonium phosphate, losses were decreased. In these experiments, less K was leached from the K_2CO_3 source than from KCl. Highest K leaching occurred when N was applied with K, but Gow concluded that under sugar cane, K losses were very small.

Perkins (52) studied the influence of phosphate additions on CEC. Of 40 soils studied, 31 exhibited an increase in CEC after being treated with phosphate. He postulated that the increase in CEC was due to the formation of aluminum-phosphate. The over-all effect would be similar to that observed when liming a soil containing considerable Al, and it would be anticipated that K retention should be increased.

Others have noted the tendency of K movement to be reduced when applied as K-phosphate compounds. Lutrick (36) compared the downward movement of K from KCl and $K_2CaP_2O_7$ applied to a fallow Eustis loamy fine sand. Depth soil sample cores were taken during the season to follow K movement. A portion of the results from the limed plots receiving 332 pounds of K per acre is presented in Table II. The lack of movement of K from the potassium-calcium pyrophosphate ($K_2CaP_2O_7$) is striking. Lutrick pointed out that even with the most soluble form, K did not move out of the root zone of most crops.

Thorup and Mehlich (66) studied K retention and percolation losses using various K-phosphate sources and KNO_3 . In laboratory lysimeters, percolation losses of K increased in the following order from the various sources: $KPO_3 < K_2HPO_4 < KH_2PO_4 = KNO_3$. Retention of P from meta- and orthophosphate forms when applied to homoionic soils decrease in the order: $Al > Ca > Mg > K > Na = NH_4$. Thorup and Mehlich postulated that $Al(H_2O)_3(PO_3)_3$ could be formed, as well as $Al(OH)_2H_2PO_4$. This precipitation of Al would increase the exchange capacity, producing the same effect observed by Perkins (52).

PELLET SITE EFFECTS. Bouldin *et al.* (5) studied the effect of associated salts on transformations of monocalcium phosphate monohydrate (MCP) in fertilizer pellet site chemistry. Their research indicated that when $CaH_4(PO_4)_2 \cdot H_2O$ (MCP) is associated with K_2SO_4 about 31% of the added K was retained as residue at the pellet site as $K_2Ca(SO_4) \cdot H_2O$ (syngenite). Solution of residues from $KNO_3 + MCP$ and $KCl + MCP$ contained only traces of K. These authors found that $KCl + MCP$ reaction products initially form $Ca_2KH_7(PO_4)_2 \cdot 2H_2O$, which would bind K until $CaHPO_4 \cdot 2H_2O$ is finally formed through further leaching.

Lindsay and Stephenson (32), using metastable triple-point solution (solution from monocalcium phosphate monohydrate) in a slightly calcareous Rosebud loam, found Fe and Al precipitates which contained K. One such precipitate was identified as a K bearing taranakite mineral and the other as a complex iron-aluminum phosphate. Thus, it is apparent that K can be retained in a variety of ways when applied with phosphates.

PARTICLE SIZE. DeMent and Stanford (11) studied the influence of particle size of K sources having various solubilities on the leachability of K using small, short term uptake containers. Using -6 + 9 and -35 mesh KCl and fused KPO_3 , varying in water solubility from 7 to 96%, a particle size-solubility interaction was found. Low solubility and coarser particle size reduced loss of K. When the solubility reached 30%, the results were reversed. Increased soil-fertilizer reaction time caused an increase in K removal from the low solubility materials, but a reduction from material with higher water soluble K.

Pritchett and Nolan (49), working with greenhouse lysimeters found increased K uptake and increased movement of K from -3/8 inch +4 mesh particles when compared to finer particles of KCl 100% soluble. In one experiment, following two harvests and a leaching, as much as 50% of the K applied as fused $K_2CaP_2O_7$ was re-

Table II. Distribution of K from Limed Plots 8 Months after Receiving 332 Pounds of K per Acre as Muriate of Potash and $K_2CaP_2O_7$

(Eustis loamy fine sand. Rainfall = 42.5 inches)

Soil Depth, Inches	Exchangeable K, Pounds per Acre	
	KCl	$K_2CaP_2O_7$
0-6	155	186
6-12	160	57
12-18	144	32
18-24	81	26
24-30	36	22

Table III. Percentage of K Released from KCl as Related to Coating Thickness

Coating Thickness	First Week	Third Week	Sixth Week	Ninth Week
Light	58.2	8.0	3.8	1.1
Medium	46.8	10.2	4.9	1.5
Heavy	12.8	7.8	10.3	6.0

covered from undissolved particles, while recovery of K from fused KPO_3 was from 20 to 40%. Also, the most uniform K uptake by several harvests of a sequence of millet, oats, and millet grown on the same plots was from the -3/8 inch +4 mesh fused KPO_3 (13% water-soluble K) and $K_2CaP_2O_7$ (7% water-soluble K) sources.

Lunt and Kwate (35) have used a K frit material (~29.8% K) produced by fusing orthoclase, feldspar, and KNO_3 or K_2CO_3 . Increasing particle size from 200 mesh to -28 + 48 mesh showed a marked reduction in the rate of solution, both in water and soils. They propose this type of K carrier for use on specialty crops to release K over a long period of time.

Tisdale (67) has indicated that research is underway to evaluate the slow release of K from a material containing K in a matrix of fused sulfur. The principal advantage of such a product, as well as other slowly releasing products, will be that larger single applications can be made without danger of salt effects or loss (48).

COATED PARTICLES. Lawton (30) reported that plastics, resins, and other substances, including polyethylene, vinyl acetate, acrylic resins, wax emulsions, waxes, and asphaltic, as fertilizer coatings were being investigated. Lawton reported difficulty in coating granules of KCl without making them completely insoluble. However, mixed fertilizers such as 0-8.7-16.6 (0-20-20) and 5-8.7-16.6 (5-20-20) were relatively easily coated because of the porous rough nature of the granule surface.

In an alfalfa-topdressing field experiment, Lawton (30) found that release

of K was controlled to a degree by coating and provided improved seasonal distribution of the K in the alfalfa.

As part of the same experiment, Lawton recovered the fertilizer granules and determined the K remaining after weathering. About 1 month after application, essentially none of the K remained in the uncoated granules, while over 10% remained in the coated granules.

Cerli and Lunt (50) used coating membranes of varying thicknesses on KCl particles to study K release (Table III). The effect on the rate of release of K is apparent. These authors noted that soil reaction did not influence movement of K from coated granules, but that increasing soil temperature from 10° to 20° C. doubled the rate of K release. The authors also found that coated K material topdressed released 30 to 50% less K than that incorporated uniformly through the soil.

Rainfall Intensity, Duration, and Frequency. PERCOLATION AND RUNOFF. Rainfall intensity, duration, and frequency all play an important role in the amount of water moving through the soil profile. Soil texture and structure, as well as soil cover as they affect infiltration, will have major influences. Most of the water from an intense rain of short duration may be lost as runoff. However, a rain of low intensity but long duration may produce little runoff and a large amount of percolate.

Runoff and percolation from various soil series located at the same site in monolith lysimeters provide insight into how differently soils absorb moisture under similar conditions of rainfall (63). A comparison of the year to year differences for the Muscatine series showed wide variations in runoff and percolation.

Even though fairly large amounts of percolate passed through some of the soils studied (63), only a very low amount of native soil K was removed. A comparison of the amounts of Ca, Mg and K found in the percolate after a 3-year and an 8-month period is shown in Table IV.

As might be expected when runoff is not permitted, moisture movement through the profile should increase, making leaching of nutrients more probable. However, Kilmer *et al.* (27) evaluated loss of native soil K from a Fayette silt loam and found that even without runoff in fallowed monolith lysimeters annual K losses amounted to only 2.4 pounds per acre.

Surface runoff can transport nutrient elements. Duley (14) checked the amount of K in surface runoff with and without a crop cover for 1 year with a rainfall of 45.2 inches. The annual loss without cover and spaded 4 inches deep was 7.7 pounds of K per acre, while with cover the loss was only 1.6 pounds

Table IV. Pounds per Acre of Ca, Mg, and K in the Percolate of Three Illinois Soils for a 3-Year and an 8-Month Period

Soil Series	Ca	Mg	K	Perco-
				late, In.
Tama	192.2	102.1	2.5	13.0
Muscatine	311.4	175.0	5.0	23.0
Edina	139.9	74.5	2.7	10.2

per acre. In many cases, losses might well be higher than these.

Midgley and Varney (46) conducted K runoff field plot studies in Vermont to evaluate loss of K from manure treatment. They found losses from 10-ton applications of manure were from 19.2 to 27.4 pounds of K per acre per year, depending upon the topography.

An average annual water surplus map for eastern United States was prepared by Nelson and Uhland (47). The amount of water remaining after evaporation has been deducted would be surplus and could be lost by percolation and runoff. Relatively high rainfall and centuries of percolation through the soils of the eastern United States helped to remove K. This is in contrast to the lower surplus water and percolation and hence lower K removal in the Great Plains.

Crops Grown, Soil Cover, and Mulches. Lysimeter and soil sampling work (1, 27, 37, 56, 70, 72) has shown reductions of K movement when soils are cropped. The amount of reduction will vary with the crop grown. Volk (72) found that applied K losses on sandy soils over an 8-year period were reduced from 20 to 3.1% by using a winter legume in the rotation.

Volk and Bell (70) noted that when 83 pounds of K per acre was broadcast on Norfolk loamy fine sand, a crop of turnips as compared to fallow reduced the K in the leachate. The values were 0.8 and 3.3 pounds of K per acre, respectively. With a rate of 45 pounds of K, K uptake accounted for 118% of that applied. In subsequent work on the same lysimeters, they found that even under fallow, K losses did not exceed 8% of that applied (71).

Pritchett and Nolan (56) used cabbage and oats as winter crops and sweet potatoes and millet as summer crops. The oats and millet reduced the K in the leachate more than the cabbage and sweet potatoes. The reason for this is undoubtedly the fibrous root system of grasses. A comparison of the K measured in the percolate under fallow and the oat-millet sequence for the various K applications is shown in Table V. On sandy soil, a crop will reduce K movement much more than would be

Table V. K in Percolate with Three K-Rates under Fallow and an Oat-Millet Crop Sequence

(Arredondo Fine Sand)

K Applied, Lb./Acre	K in Percolate, Lb./Acre	
	Fallow	Oats-millet
100	32	3.0
199	48	4.2
398	156	9.4

inferred from the amount of percolate passing through the profile. For example, a 25% reduction in percolate produced a 76% reduction of leached K from the cabbage-potato plots. Allison *et al.* (7) found reductions in K loss as high as 85% with certain combinations of crops grown over a period of time.

Straw, forage, or hay mulches frequently have been used in orchards to control weeds and reduce moisture loss and runoff. In as much as plant K is water soluble, over a period of years considerable K will be added. Wander and Gourley (74) took soil samples in an orchard experiment of which portions had been heavily mulched for many years. It was estimated that in one case 2400 to 3200 pounds of K per acre had been added under mulched trees. Over a 22-year period, exchangeable K was greatly increased down to the 32- to 40-inch depth.

Discussion of Lysimeter Studies. According to Joffe (22), data from shallow, filled-in type lysimeters should be carefully evaluated. Regarding the use of these lysimeters, Joffe stated "... the method with the filled-in type of lysimeters is irrational and the findings of such data cannot be applied to soil conditions. The leaching from such lysimeters give no picture of what is going on in the soil, for they do not contain the heterogeneous soil body." This author was particularly critical of the early Cornell and Tennessee work. In the same paper, Joffe described a type of lysimeter for studying leaching losses through various soil horizons *in situ*, which was of the Ebermayer type (28). In a subsequent study Joffe (23), found that only 1% of the leachings passed through the B horizon of the soil.

It would seem that differences found between a filled-in lysimeter and a profile-monolith or Ebermayer type would depend to a large degree on soil texture and amount of profile development. For example, on very sandy soils or relatively unweathered soils differences should not be great, unless soil structure or compacted layers are markedly changed by crushing or screening. Where such is the case, K movement might be great early in the trial, but

be reduced due to impeded drainage at a later date. Joffe (22) reported that such was probably the case in the Cornell work because water was impounded on the surface of the lysimeters. Too, no provision was made for runoff. Truog and Jones (68) also were critical of the latter work. However, certain maxima for K movement are obtained, which when combined with the field profile measurements provide a means of estimating movement of elements.

Tension plate, Ebermayer type lysimeters such as used by Krause and Wilde (29) to study K leaching under pine seedlings may be the kind that will come into use. The K found in the leachate from 100 pounds of K as KCl, using tension plates placed at only 18 inches, was only 17.5 pounds per acre more than the control.

If this type of lysimeter were used, it is possible that field studies could be conducted, and by using the Gapon equation recently applied by Thomas and Coleman (64), K retention for various soils could be predicted quite accurately.

Lutrick (36) has cautioned about the use of short leaching tubes in laboratory studies, but work does indicate meaningful results can be obtained (20, 44, 64, 76). However, the best information will probably be obtained in the field if proper precautions are taken.

Potassium Found in Field Profile Samples. Thomas and Schueler (65) conducted a profile sampling study to an 18-inch depth on commercial orchard soils representing five series ranging in texture from a sand to a clay loam and with CEC ranging from 1.55 to 8.55 meq./100 grams. Under rather high rates of K applied over 4 years, in some instances exchangeable K in the 0- to 6-inch samples occupied over 30% of the exchange complex. Exchangeable K data for three soils receiving N alone and a total of 352 pounds of K applied as KCl over a 4-year period are presented in Table VI.

Thomas and Schueler concluded that on coarse-textured soil it would be well to know the exchange capacity and use moderate applications of K applied more frequently on those soils having low CEC. In their work, even though some K undoubtedly moved below 18 inches in the coarser-textured soils, increase in exchangeable K and crop removal should have accounted for most of the K applied.

Pratt and Goulben (54), working with a Ramona sandy loam under citrus that had been irrigated and fertilized with various rates of K, studied the exchangeable K in the profile after 28 years of treatment. The authors concluded that for rates of K up to 400 pounds per acre per year, all of the K can be assumed to have remained in the top 2 feet, and for higher rates it can be

Table VI. Exchangeable K in Three Soil Types Sampled to 18 Inches with and with K Applied during a 4-Year Period

Soil Depth, Inches	Lb./Acre Exchangeable K in:					
	Sassafras loamy sand		Manor loam		Berk silt loam	
	No K	352 Lb. K/acre	No K	352 Lb. K/acre	No K	352 Lb. K/acre
0-6	57	115	143	845	181	586
6-12	62	146	57	181	93	316
12-18	63	127	63	103	93	103

assumed to have stayed in the top 3 feet. These data reflect a parallel to K lysimeter irrigation data presented by Broadbent and Chapman (6). The latter found that K in the leachate from Sierra loam over a 15-year period amounted to only 1 pound of K per acre per year.

Doll *et al.* (73) and Wells and Parks (75) studied the distribution of exchangeable K after a number of years of K application at several rates on forages. Doll *et al.* found that on a Pembroke silt loam annual applications of 50 and 100 pounds of K per acre indicated only slight K accumulation in the 0- to 1-inch layer, and that applications of 398 pounds of K per acre did not result in increases in exchangeable K below the 0- to 6-inch layer. A yield of over 5 tons of hay per acre, containing 320 pounds of K, was obtained in this experiment.

Wells and Parks (75) followed soil test recommendations in fertilizing various soils for establishing alfalfa. In subsequent years, K was topdressed annually. Data on the distribution of K in the profile for a Maury silt loam are presented in Table VII for three levels of K after 5 annual applications. Results indicate little K movement into the 12- to 18-inch depth. With the exception of a Dunsmore soil, most of the K could be accounted for in the 0- to 12-inch depth.

In a thorough experiment on sweet potatoes on a Norfolk loamy sand, the distribution of K in the soil profile was followed during the season (27). A K balance sheet approach was used, determining the amounts taken up by the crop and the amounts in the soil at different dates. Rates up to 468 pounds of K per acre were applied. At the 199-day sampling (harvest), soil and plant K more than accounted for the K applied at the 117 and 234 pound per acre rates of K. Eighty-four pounds were unaccounted for at the 468-pound rate. This may have been below the depth sampled. Such K efficiency on a sandy soil with an exchange capacity of only 2 meq./100 grams is certainly an indication that little leaching below the depth of rooting occurred.

Crop response to residual fertilizer indicates increases in K soil level when

Table VII. Available K at Various Depths after Five Annual Topdressings on Alfalfa

(Maury Silt Loam)

Soil Depth In.	Annual K Rate, Lb./Acre		
	None	166	332
		p.p.2m.	p.p.2m.
0-1	105	350	640
3-6	46	126	366
12-18	63	84	89

K is applied at adequate rates (9). This is true on organic soils (10) as well as on mineral soils. Work on muck using sewage effluent supports the fact that K leaching is not a serious problem (60) on some such soils.

Potassium Fixation. Potassium fixation, as far as reducing K movement is concerned, is an asset. DeTurk *et al.* (12) indicated that fixation decreased the loss of applied K in drainage water. To study the phenomenon of fixation on K retention, the authors applied rates of KCl as high as 20 tons per acre. Qualitative tests indicated that during 3 years, vertical penetration and accumulation of K had occurred at least to the B horizon (probably about 20 inches). Where one tone of KCl (996 pounds of K) per acre was applied to a lysimeter (5 feet deep) in which runoff was prevented, no excess K appeared in the drainage water during a 12-month period.

Wicklander (77) has stated concerning K fixation, "Fixation and defixation act as a valuable buffering mechanism in the soil. At high concentrations of K_s ($K_s = K$ in the soil solution), the level is lowered by fixation, thus minimizing the losses by leaching. At low K_s levels, on the other hand, the soil is able to supply plants with more K than is possible without the reserve of fixed K." Thus, as Schuffelen and van der Marel (58) and others have indicated, K fixation does retard K movement.

Practical Implications

On silt loam or heavier-textured soils, loss of K by leaching is negligible. However, on sandy soils considerable leach-

ing may occur under some conditions.

From the material reviewed, several points of practical significance regarding the reduction of K movement in coarse-textured soils are apparent. Among these are tillage, liming, application of elements other than K, source of K, and placement and rate of fertilizer K used.

For soils requiring lime, perhaps the first step should be to apply lime to adjust soil pH to 6.5 well ahead of K fertilization. Thorough mixing of the lime in a deep plow layer is desirable. This is particularly important in soils that contain considerable aluminum. Liming should increase the CEC and the soil's capacity to retain K.

The sequence of leachability of various sources of K appears to be $KCl = KNO_3 > K_2SO_4 > KH_2PO_4 > K_3HPO_4 > K_3PO_4 = KPO_3 > K_2CaP_2O_7$. While K in the form of K_2CO_3 would be readily retained initially on the exchange complex (19) and may actually be more tightly held than that of KPO_3 (49), Gammon (17) has indicated that this source must be used with discretion or deflocculation of the soil colloidal system may occur. If KPO_3 and $K_2CaP_2O_7$ are fused, of low solubility, and of large particle size, it is probable that K leaching would be reduced even more. Also, evidence would indicate that perhaps K applied in a mixed fertilizer might initially be less susceptible to leaching than that applied as a straight material.

For sandy soils, topdressing the K carrier on the soil surface should decrease the rate of movement of K into the soil. This would be particularly true of slowly soluble, coarse granular or coated K fertilizers.

On finer-textured soils on sloping or rolling land, it should be advantageous to plow-down K when heavy applications are applied in order to prevent surface losses. Minimum tillage and plow-plant operations for corn on silt loam soils have reduced soil and water runoff loss. Some row K should be used unless soil K levels are very high as the efficiency of recovery is in its favor over broadcast K.

On very sandy soils, a crop should be kept on the soil as much of the time as possible. Solid plantings of grass and legume crops should reduce K losses the most. Spring plowing and application of K as close as possible to the planting date or period of utilization should be helpful in recovery of applied K. Gammon (17) indicates that for crops requiring large amounts of K and grown on light-textured soil the major source of K is that applied as fertilizer rather than that from the exchange complex. Work conducted in North Carolina (27) substantiates this.

On light textured soil periodic side-dressing of cotton with K along with N

Table VIII. Influence of Fertilization on "Available" Moisture, Depth of Corn-Root Penetration, and Corn Yields

Series	Available Moisture Holding Capacity to Rooting Depth, Acre-Inch	Depth of Root Penetration, Inches	Corn Yield, Bu./Acre
Muscatine, fertilized	17.4	66	81
Cisne, unfertilized	11.7	40	20
Cisne, fertilized	17.3	60	75

from planting through the third week of fruiting is recommended in North Carolina. The rate of application recommended depends upon the amount of water passing through the root zone during the period. This indicates the importance of moderate, frequent K applications where leaching may be a serious problem.

Another factor of significance regarding the reduction of K loss is that properly fertilized crops exhibit deeper rooting depth (15, 33) (Table VIII). In Illinois research, rooting depth of corn was increased as much as 50% by fertilization. This should further contribute to recovery of K that may have moved to lower horizons. In this regard, Lutrick (36), after using rates of K up to 332 pounds per acre on sandy soil, concluded that normal applications of K would not leach beyond the rooting depth of most crops during the season.

High yields, particularly of some crops, remove large amounts of K. Hence, unless high rates of K are applied, there will be little excess K and little opportunity for downward movement.

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Kinetics of Chloride Desorption from Soils

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Chloride spreads with depth of penetration in soils resulting in an increasing vertical distribution and a diminishing average concentration. If adsorption occurs, the distribution of chloride becomes skewed rather than normal, and the length of the trailing edge is dependent upon the amount of adsorption. The peak itself does not shift, however. Washing a quantity of chloride out of a soil begins at the same rate whether the soil is a chloride adsorber or not. A break in chloride concentration vs. milliliters of wash water occurs only with materials which adsorb chloride. If the data are plotted as first-order reactions, there is a distinct break in the curve with chloride adsorbers; this second curve, if extrapolated, gives an intercept corresponding to adsorbed chloride. The intercept varies as factors influencing adsorption are varied. Plotting elution curves as first-order reactions gives the same results. Such a plot shows that the position of the peak will not shift unless all chloride is adsorbed.

WHEN a salt of chloride is placed on a soil surface and then eluted with water, its distribution in the soil at some later time will depend on a number of factors. The general tendency will be for the anion to follow the moving water front in a soil, but because velocity of the water is not uniform throughout the soil, some of the chloride will move ahead of the predicted water front and some will lag behind. In a system where saturated water flow occurs and in which the velocity of water flow is relatively fast, thus minimizing diffusion, the chloride will tend to spread out both on the leading edge and on the trailing edge. The form of the spread is like that of a normal curve and is described by the Day and Forsythe equation (3).

$$C/C^{\circ} = \frac{x^{\circ}}{(2\pi\beta\bar{x})^{1/2}} e^{-\frac{(\bar{x}-x)^2}{2\beta\bar{x}}} \quad (1)$$

where C/C° = ratio of solution concentration to original concentration
 x° = depth of added Cl solution
 \bar{x} = depth where peak concentration occurs
 x = any depth of interest
 β = a constant, determined empirically

β is called an "Index of Dispersion" by Day and Forsythe (3). Figure 1 shows this equation applied to some data for chloride distribution on coarse sand.

A β value of 0.60 was used on both the 5.2-cm. column and the 40.4-cm. column. The resulting curves show fair agreement with experimental points. If the same β value can be used in both columns, then the amount of spreading is proportional to the square root of the depth to which the chloride has moved. Even in the short column, the maximum concentration of chloride has been cut to only one-third that of the original.

Superimposed on the spreading tendency already mentioned, there is in some soils adsorption of chloride. Soils which adsorb chloride are characterized by relatively high oxide content, low cation-exchange capacity, and low pH. In such a soil, the chloride would not be expected to move along with the water.