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LEACHING OF APPLIED N, P AND K IN A TROPOFOLIST SOIL AS AFFECTED BY ROCKINESS AND ORGANIC AMENDMENTS

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ABSTRACT

Tropofolists are organic soils that develop in fragmental lava. These rocky soils are being used increasingly for agriculture in Hawaii. Variability in the proportion of fine soil and rock leads to difficulties in implementing efficient fertilizer and irrigation programs. High rainfall in areas where these soils are being farmed results in rapid leaching of applied nutrient elements. The objectives of this study were to assess the rate of leaching of N, P, and K applied to a Tropofolist soil with varying densities of the fine-earth-fraction (FEF) (<2 mm) and to evaluate the effect of surface organic layers in reducing N and K leaching. Four treatments representing 0.1, 0.2, 0.3, and 0.4 g FEF cm^{-3} were established in 20-L leaching columns with four replications. Leaching of N and K applied at 100 kg ha^{-1} was monitored over several cycles under natural rainfall. In a second trial P leaching was evaluated under more intense leaching conditions created by hand-watering. The effect of surface layers of macadamia compost and muck on N and K leaching was evaluated in a third trial. Cumulative rainfall required to leach 50% and 90% of applied N averaged 15 and 26 cm and was little affected by FEF density or organic amendment. Cumulative rainfall required to leach 50% and 90% of applied K was affected by FEF density and ranged from 21 and 52 cm for the 0.1 g cm^{-3} treatment to 44 and 70 cm for the 0.4 g cm^{-3} treatment, respectively. Compost and muck treatments had variable effects on K leaching depending upon the cycle. In one cycle, the compost layer decreased K leaching 25%. The FEF density had no measureable effect on the leaching rate of P. Only 0.7% of applied P was leached with the application of 213 cm of water. Results of these leaching studies should aid in fertilizer scheduling to improve fertilizer-use efficiency and to reduce groundwater contamination.

INTRODUCTION

Tropofolists are organic soils that develop in fragmental lava. These rocky soils are found in large areas of the Hilo, Puna, Ka'u and Kona districts of the Big Island of Hawaii where they are being used increasingly for agriculture. Although papaya, macadamia, coffee, and pasture have been traditionally the most important agricultural usages for these soils, they are also being used for the production of tropical fruit trees, flowers, foliage plants, vegetables, and other diversified crops.

One of the problems farmers face in utilizing these rocky soils is the variability in the proportions of rock and the fine-earth fraction (<2 mm). Because the fine-earth fraction (FEF) is responsible for most of the nutrient retention and water-holding capacities exhibited by these rocky soils (Periswamy, 1973), variability in the proportion of fines leads to difficulties in implementing efficient fertilizer and/or irrigation programs.

High rainfall in areas where these soils are being farmed causes rapid leaching of applied nutrient elements. Tamimi (1980) investigated the leaching potential of N, P, and K in three Tropofolist profiles reconstructed in leaching columns. A high rate of 550 kg ha^{-1} of each element was applied followed by successive leaching volumes of water equivalent to 5.1, 5.1, 10.2, and 20.3 cm of rainfall. Results indicated that 100% of the applied N but less than 3% of the applied P was leached out of the soils with the equivalent of 41 cm of water; leaching of applied K was variable ranging from 13% in a deeper profile high in fines to 56% in a shallower profile lower in organic matter. The authors concluded that organic matter management should be crucial for improving the productivity of these soils and that fertilizer scheduling should be based upon rainfall, particularly for N and K. However, no specific guidelines were given.

The objectives of this study were (1) to evaluate the effect that FEF density has on the leaching of N, P and K applied at moderate rates to leaching columns of a Tropofolist soil, and (2) to evaluate the effectiveness of surface layers of compost and muck in reducing the leaching rate of N and K.

MATERIALS AND METHODS

Soil Properties

In order to identify the range in the fines content of the tropofolist soils, a survey of the proportion of rock and FEF was made for soils at eight locations (Table 1). For each location, three separate holes approximately 46 cm x 46 cm x 46 cm were dug and the soil contents removed. The volume of the hole was measured by determining the volume of cinder (0.64 to 1.27-cm sieve fraction) required to fill the excavated hole. Excavated soil material was sieved moist at the site through 10.2, 5.1, 2.54, 1.27, and 0.64-cm screens and weighed. Subsamples of each sieve fraction were placed in plastic ziplock bags for dry weight (105°C) determinations. Each subsample was also wet-sieved through a 2-mm sieve to determine the amount of FEF associated with it. Loss on ignition (800°C) was used to estimate organic matter content.

Experiment 1: Effect of the FEF density on N and K

Based upon the ranges found in the soils surveyed (Table 1), four FEF densities were evaluated as soil treatments: 0.1, 0.2, 0.3, and 0.4 g cm^{-3} soil. Papai soil (euic, isohyperthermic, Typic Tropofolist) collected from the University at Hilo's Agricultural

Farm Laboratory was used to establish the soil treatments. Some important characteristics of this soil are given in Table 1. Treatments were established in 20-L leaching columns (radius of 15 cm and depth of 29 cm) and were replicated four times. Each column contained the equivalent of 0.2 g cm^{-3} of the 2-12.7 mm rock fraction (see Table 2); variable amounts of 12.7-50.8 mm rock fraction were used to achieve a final soil density of 1.5 g cm^{-3}. After leaching the columns with 20 L of water, the equivalent of 100 kg N ha^{-1} (710 mg N per column) as $(NH_4)_2SO_4$ and 100 kg K ha^{-1} as KCl were applied uniformly on the surface. Fine, granular, reagent-grade chemicals were used. The soil columns were placed outside at the University of Hawaii at Hilo's College of Agriculture. Rainfall was recorded daily and leachate samples were collected after every 2.5 or more cm of total rainfall had fallen. Leachate volumes were determined by weighing. Subsamples were analyzed for NO_3-N and NH_4-N by the two-step ammonia distillation procedure using MgO and Devarda's alloy (Bremmer, 1990). Potassium was determined by atomic absorption spectrophotometry. Three cycles of N and two cycles of K application and leaching were completed.

Analysis of variance was used to evaluate the effect of treatments on the amount of rainfall required to leach 50% and 90% of the applied N and K from the soil columns. A split-plot design was used with treatments serving as main plots and cycles serving as split-plots.

Experiment 2: Leaching of P

The soil columns from Experiment 1 were used to evaluate the leaching of P applied at 3520 mg P per column (500 kg P ha^{-1}). Screened (>1.0 mm) concentrated superphosphate (20% P) was used as the fertilizer source. The columns were placed under shelter and 2.54 cm of tap water were applied daily except weekends. Leachate was collected after every five applications of water (12.5 cm total water applied) and analyzed for orthophosphate using ammonium molybdate-ascorbic acid methodology (Olsen and Sommers, 1982). The experiment was terminated after 17 leachate collections. The effect of FEF density on cumulative P leached and average leachate P concentration was assessed with ANOVA using a randomized complete block design.

Experiment 3: Effect of Organic Amendments

Twelve soil columns each with a FEF density of 0.2 g cm^{-3} were established as described in Experiment 1. Three treatments were evaluated: 1) control, 2) 5 cm surface layer of muck (740 g oven-dry equivalent per column), and 3) 5 cm surface layer of macadamia nut compost (524 g oven-dry equivalent per column). The muck was collected from an old, established macadamia orchard (Mauna Loa Macadamia Nut Corp., Kea'au) where decomposing leaf litter commonly accumulates to form surface layers of muck and fine soil. The macadamia compost, which was obtained from Puna Macadamia Co., Kea'au, was taken from a 6 month old compost pile of well-decomposed macadamia shells and husks. Selected characteristics of these organic materials are provided in Table 1. The soil columns were placed outside and leachate was collected and analyzed for N and K as described in Experiment 1. Nitrogen and K were applied as described for Experiment 1 except for the first cycle when K was applied mistakenly at the equivalent rate of 238 kg K ha^{-1} instead of the desired rate of 100 kg K ha^{-1}. Results were analyzed statistically as described in Experiment 1.

RESULTS AND DISCUSSION

Soil Properties

The particle-size distributions of eight Tropofolist soils are given in Table 1. The FEF of the soils ranged from 0.07 g cm^{-3} to 0.39 g cm^{-3}. Periswamy (1973) reported average FEF densities of several tropofolist to be approximately 0.1 g cm^{-3} with a few horizons exhibiting as high as 0.7 g cm^{-3}. Because typical soils without rocks have soil densities ranging from 1 to 1.5 g cm^{-3}, a given volume of Tropofolist soil may contain 5-30% of the FEF contained by typical soils. And, although the sum of exchangeable cations reported in Table 2 would be considered typical for productive, agricultural soils, low FEF densities result in very low cation retention properties of these soils when considered on a volume basis.

The distribution of the rock fractions indicated that approximately 20% of the rock fraction (>2 mm) was less than 12.7 mm. The density of this fraction ranged from 0.05 to 0.41 g cm^{-3} with a mean of 0.22 g cm^{-3}. Although comparatively inert chemically, this fraction was reported to exhibit some water retention properties, especially at low tensions (Periswamy, 1973).

Experiment 1: FEF Density

Nitrogen. The observed pattern of N leaching following the application of 100 kg N ha^{-1} during the first cycle (Fig. 1) is typical of the patterns observed during the second and third application cycles. Rapid losses in N were observed during the period of time when 5 cm to 25 cm of cumulative rainfall had occurred. The amount of rainfall associated with the leaching of 50% of the applied N ranged from 14.2 cm for the 0.1 g FEF cm^{-3} treatment to 17.2 cm for the 0.4 g FEF cm^{-3} treatment (Fig. 2). These values represent the average of the three cycles; there were no significant ($p<0.05$) cycle or cycle-by-treatment effects. By the time 90% of the applied N had been leached, no significant ($p<0.05$) treatment differences were observed. However, the rainfall required to leach 90% of the applied N depended upon the cycle ($p<0.05$) and was 24.1, 28.3, and 31.0 cm for the first, second, and third cycles, respectively. When averaged over the three treatment cycles, 27.8 cm of rainfall were required to leach 90% of the applied N.

The more rapid initial leaching of N observed in the low FEF density treatment can be attributed in part to the greater leaching of NH_4-N (Fig. 3). Ammonium-N accounted for an average of 13% of the

N leached in the low FEF density treatment but only 1% in the high FEF density treatment. These percentages were consistent for each of the three cycles. Greater retention of ammonium, the form of N applied, by the higher FEF density treatments was likely due to greater cation exchange capacities associated with increasing FEF densities. Even for the low FEF density treatment, the leaching of NH_4-N became insignificant after approximately 15-20 cm of rainfall or approximately 50% of the N had leached. Apparently by this time most of the NH_4-N had been nitrified to NO_3-N which was readily leached in all treatments and which resulted in treatments having insignificant effects by the time 90% of the applied N had been leached.

One might suspect that lower FEF densities may lead to greater leaching volumes and, hence, greater leaching rates. This was not the case as treatments had no significant ($p<0.05$) effect on the quantity of leachate collected. The fraction of rainfall collected as leachate when averaged over all cycle-treatments was found to be 0.61, ranging from 0.49 to 0.70.

Leachate N concentrations associated with the leaching of 90% of applied N are given in Table 3. Mean and maximum concentrations were 56 and 99 mg L^{-1} for NO_3-N and 60 and 106 mg L^{-1} for total N (NO_3-N + NH_4-N); no significant ($p<0.05$) treatment effects were observed. Treatments had a significant effect ($p<0.01$) on the mean NH_4-N leachate concentration. A linear equation, $Y = 15.9 - 39.8x$ ($r^2=0.73$) could be used to predict the mean NH_4-N leachate concentration during an application cycle (Y in mg L^{-1}) based upon the FEF density (x in g cm^{-3}).

Leachate concentration values for NO_3-N exceeded the maximum allowable NO_3-N level in drinking water of 10 mg L^{-1} established by the USEPA (Smith et al., 1991). Therefore, results indicate that leaching of fertilizer N in Tropofolist soils in high rainfall areas is a potential source of groundwater pollution.

Potassium. The first cycle of K application and leaching is given in Fig. 4; cycle and cycle-by-treatment effects were not significant ($p<0.05$). When averaged over two cycles, the rainfall required to leach 50% of applied K was 21, 30, 38, and 44 cm for the 0.1, 0.2, 0.3, and 0.4 g FEF cm^{-3} treatments, respectively (Fig. 2). For the same treatments, rainfall required to leach 90% of the applied K was 52, 59, 61, and 70 cm, respectively. Unlike results observed with N, FEF density had a significant ($p<0.05$) effect on the amount of rainfall required to leach 90% of the applied K.

Leachate K concentrations are given in Table 3. Mean leachate K concentration per application cycle ranged from 10.8 mg L^{-1} for the low FEF density treatment to 16.6 mg L^{-1} for the high FEF density treatment. Maximum leachate K concentrations ranged from 40 to 60 mg L^{-1} and were observed between approximately 20 and 30 cm of cumulative rainfall.

Experiment 2: FEF density and Phosphorus

Cumulative P leached after applying 216 cm of water to the soil columns was not significantly ($p<0.05$) affected by FEF density. Therefore, the average effect of all treatments on cumulative P leached is plotted in Fig. 5. After the cumulative application of 213 cm of water, an average of only 0.7% of the applied P had been leached out of the columns. Approximately one-half of the P that was leached during the experiment was leached out during the first 25 cm of water applied. Thereafter, leachate P losses remained constant at approximately 0.06 mg P per cm of applied water per column. This is equivalent to approximately 0.0086 kg P ha^{-1} cm^{-1} water. In other terms, 1 kg P ha^{-1} would be leached below a 29 cm depth of this soil with every 116 cm of applied water.

Leachate P concentrations decreased from an average high of 0.6 mg P L^{-1} for the first leachate collection to an average 0.07 mg P L^{-1} for the last four leachate collections (Fig. 6). Leachate collected prior to P fertilization contained less than 0.008 mg P L^{-1}. Soluble P concentrations greater than 0.01 mg L^{-1} have been associated with eutrophication in certain water bodies (Smith et al. 1991).

Experiment 3: Effect of Muck and Compost

Nitrogen. Muck and compost layers on the surface of the Tropofolist soil had no effect on the rainfall required to leach 50% and 90% of applied N (Table 4). There was a significant cycle effect such that leaching was much faster in cycle 3 than in cycles 1 or 2. The relatively low values in cycle 3 are attributed to an uncommon drought which lasted for 7 weeks after applying the fertilizer. Apparently all the applied N had been nitrified during the 7 wk period before leaching rains arrived as no NH_4-N was recovered in the leachate, only NO_3-N. As observed with FEF density treatments, neither muck nor compost treatments had an effect ($p<0.05$) on leachate volume.

An interesting result that was only observed with cycle 1 was that a high percentage of N was leached as NH_4-N (38% for the control treatment). This is considerably higher than the average 8% observed for the 0.2 g FEF cm^{-3} treatment in Experiment 1. The higher percentage of leachate NH_4-N may be due to the higher rate of K that was applied mistakenly during the first cycle. A greater K concentration may have limited NH_4-N retention on cation exchange sites thereby increasing the potential for NH_4-N leaching.

Potassium. The effects of compost and muck treatments on the leaching of K depended upon the cycle (Table 5). During the first cycle, the surface layer of compost had no effect on the leaching of K. Rainfall required to leach 50% and 90% of the applied K averaged 44 and 86 cm for the compost and control treatments, respectively. These figures are higher than those reported in Experiment 1 and are attributed to the higher rate of K applied in cycle 1 of Experiment 3 (238 vs. 100 kg K ha^{-1}). The rapid leaching of K from the muck treatment may have been confounded by high K levels in the muck (Table 2) as almost twice as much K was leached out the muck treatments than was applied. In order to minimize this K-supplying effect of the muck treatment, leaching was allowed to continue until leachate K concentrations from the muck treatment were low (<5 mg L^{-1}) before initiating the second cycle.

In the second cycle, the compost layer decreased the leaching rate of applied K. Compared to the control, the compost treatment required higher rainfall to leach 50% of applied K 21% (29 vs. 24 cm) and 90% of the applied K 25% (65 vs. 52 cm). The muck treatment had no significant effect on the same measurements in the second cycle.

The reason that the compost treatment had an effect in the second but not the first cycle is difficult to explain. One explanation is based upon the 7-wk drought period that occurred after applying the K (same as the third N cycle in Experiment 1). In the first cycle rainfall may have leached the K below the compost layer before it was adsorbed to a large extent onto the cation exchange sites of the compost. The extended dry period experienced in the second cycle may have allowed the K to be adsorbed more effectively on the cation exchange sites of the compost.

CONCLUSIONS

Neither the FEF density nor surface layers of compost or muck had much effect on the leaching of N in the Tropolist soil. When averaged over Experiments 1 and 3, 15 and 26 cm of rainfall were required to leach 50% and 90% of the applied N out of the 29-cm deep columns. Thomas (1970) reviewed nitrate leaching literature and reported half of NO_3-N applied to fallowed soils to leach at the approximate rate of 2 cm depth per cm of rain in sandy surface soil but only 0.8 cm depth per cm rain in finer-textured surface soil and subsoil. Results for the tropofolists were approximately 2 cm depth per cm of rain which was comparable to the sandy soil. Although plant and water uptake of N should reduce the leachate N losses in the field, results reported herein indicate that frequent applications of soluble fertilizer N at low rates would be required to maximize plant-use efficiency and to minimize groundwater pollution in many rainy areas where these soils are being farmed.

Depending upon the FEF density, K leached approximately 2 (low FEF density) to 2.5 times (high FEF density) slower than N. Although results may have been confounded by K added with the muck and compost, addition of compost to the surface of the rocky soils reduced the leaching of K 25% in the second cycle. Therefore, results indicate that the addition of compost to the tropofolist soils may improve K, but not N, fertilizer-use efficiency.

Phosphorus is generally regarded as an immobile element in soils as it forms relatively insoluble compounds with Ca, Al, and Fe. Exceptions are for sandy soils (Barrow, 1980) and organic soils low in inorganic constituents (Lucas, 1982). For the latter soils, leachate P concentrations greater than 10 mg L^{-1} were observed after P fertilization. Because leachate P concentrations in the tropofolist treatments were relatively constant at only 0.06 mg P L^{-1} (or 0.0086 kg P ha^{-1} cm^{-1} water), leaching does not appear to be a fertilizer management problem. On the other hand, because P was found to be leaching in these soils at all, it follows that excessive P fertilization should be avoided to minimize potential fertilizer P loading to groundwater.

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Table 1. Particle size distribution of selected tropofolists.[†]

	Size fraction (mm)					
Soil	<2	2-12.7	>12.7	<2	2-12.7	>12.7
	% dry-wt. basis			------ g cm^{-3} ------		
Papai 1	13	7	80	0.22	0.20	1.36
Papai 2	16	12	72	0.26	0.18	1.12
Papai 3	15	10	75	0.26	0.17	1.26
Keaukaha	24	20	56	0.37	0.31	0.89
Kiloa	23	23	54	0.30	0.31	0.74
Keei	21	16	63	0.31	0.23	0.90
Malama 1	15	16	69	0.23	0.23	1.03
Malama 2	11	11	78	0.12	0.11	0.92
Average	17	14	68	0.26	0.22	1.03
Low	6	6	51	0.07	0.05	0.55
High	34	24	86	0.39	0.41	1.44

[†] All soils sampled were in taken in agricultural production areas. Values represent the average of three samples.

Table 2. Selected characteristics[†] of the Papai soil (<2 mm) ,compost and muck used in the leaching experiments.

		Exchangeable cations				FEF composition		
Material	pH	Ca	Mg	Na	K	OM	Sand	Si+Cl
		----- cmol(+) kg^{-1} -----				--- g kg^{-1} ---		
Papai soil	6.1	5.7	1.4	0.32	0.06	91	837	72
Compost	5.8	23.1	1.5	0.30	0.68	359	-	-
Muck	5.0	4.6	3.8	0.28	1.17	295	-	-

[†] Water pH (1:1); 1 M NH^{4}OAc extractable cations; OM by loss on ignition (800°C); si+cl = silt + clay.

Table 3. Leachate N and K concentrations associated with the leaching of 90% of the N and K applied at 100 kg ha^{-1} to a Tropofolist soil with varying densities of the fine-earth fraction (FEF).†

FEF density	NH_4-N		NO_3-N		NH_4-N + NO_3-N		K	
	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.
g cm^{-3}	mg L^{-1}							
0.1	8.7	32.0	56	96	64	107	16.6	60
0.2	4.7	16.1	54	99	59	108	15.1	47
0.3	1.8	7.9	58	101	60	103	13.6	48
0.4	0.6	1.0	57	100	57	104	10.8	40

† Values represent the average of three cycles of N application and leaching. Rainfall, leachate and average N concentrations were based upon the cycle ending when 90% of the applied N was recovered.

Table 4. The amount of rainfall required to leach 50% and 90% of N applied to Tropofolist soil as affected by a 5-cm surface layer of muck or compost.

Treatment	Rainfall to leach 50% of applied N			Rainfall to leach 90% of applied N		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
	Cumulative rainfall, cm					
Control	20	19	7	29	33	14
Muck	18	15	7	26	34	15
Compost	16	18	9	25	29	19
Cycle mean	19 a	17 a	8 b	27 x	32 x	16 y

† Means in a row for each variable followed by the same letter were judged not significant according to $LSD_{0.05}$.

Table 5. The amount of rainfall required to leach 50% and 90% of K applied to Tropofolist soil as affected by a 5-cm surface layer of muck or compost.

	Rainfall to leach 50% of applied K		Rainfall to leach 90% of applied K	
Treatment	Cycle 1	Cycle 2	Cycle 1	Cycle 2
	----- Cumulative rainfall, cm ------			
Control	43 a[†]	24 b	85 a	52 b
Muck	33 b	22 b	50 b	46 b
Compost	45 a	29 a	88 a	65 a

[†] Means in a column followed by the same letter were judged not significant according to $LSD_{0.05}$.

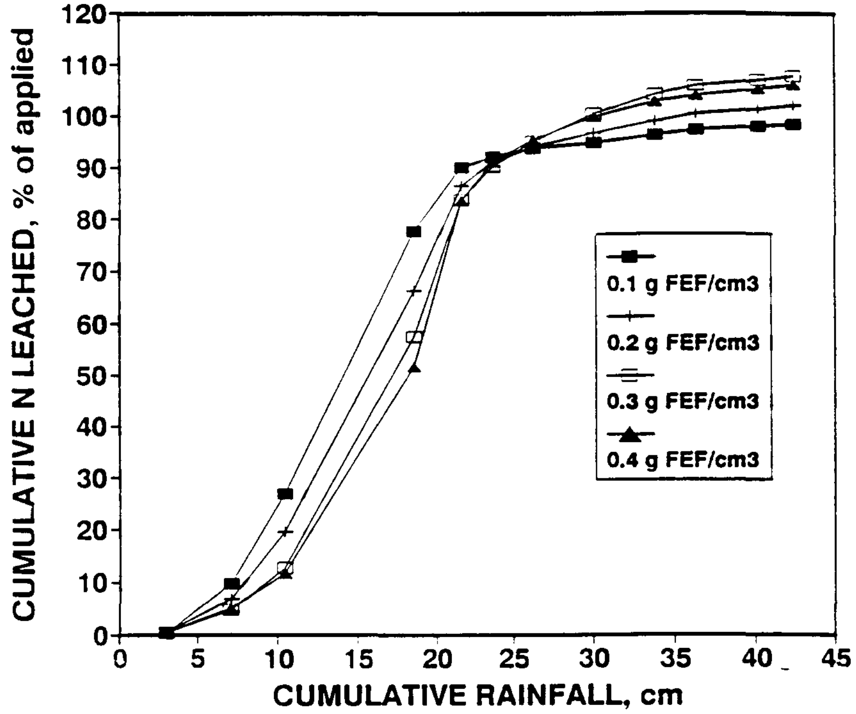

Fig. 1. Relationship between rainfall and the leaching of N applied to Tropofolist soil as affected by the density of fines (<2 mm).

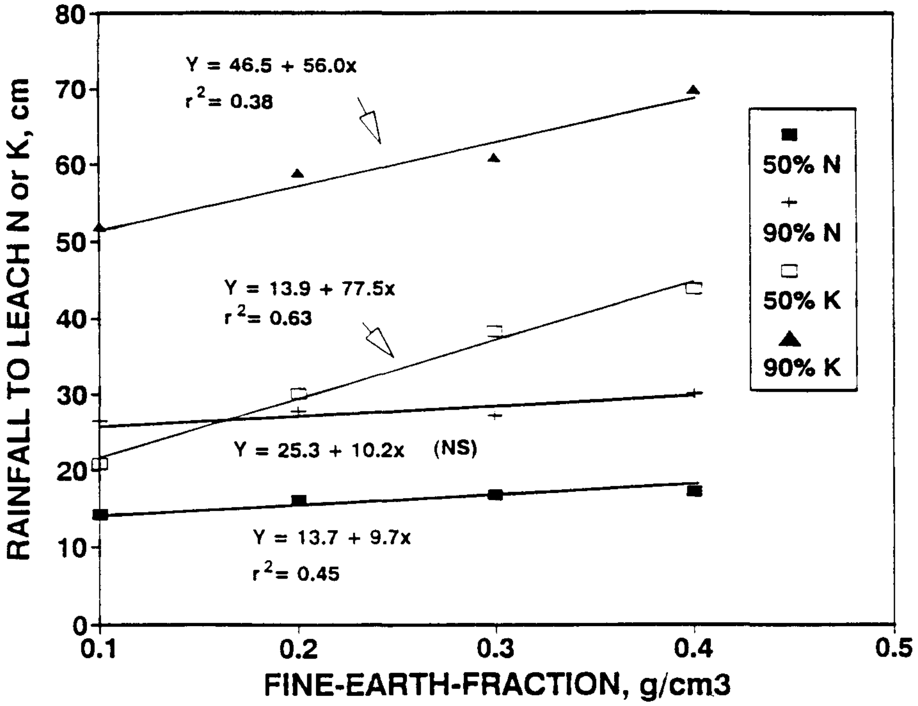

Fig. 2. The amount of rainfall required to leach 50% and 90% of N and K applied to Tropofolist soil as affected by the density of fines (<2 mm).

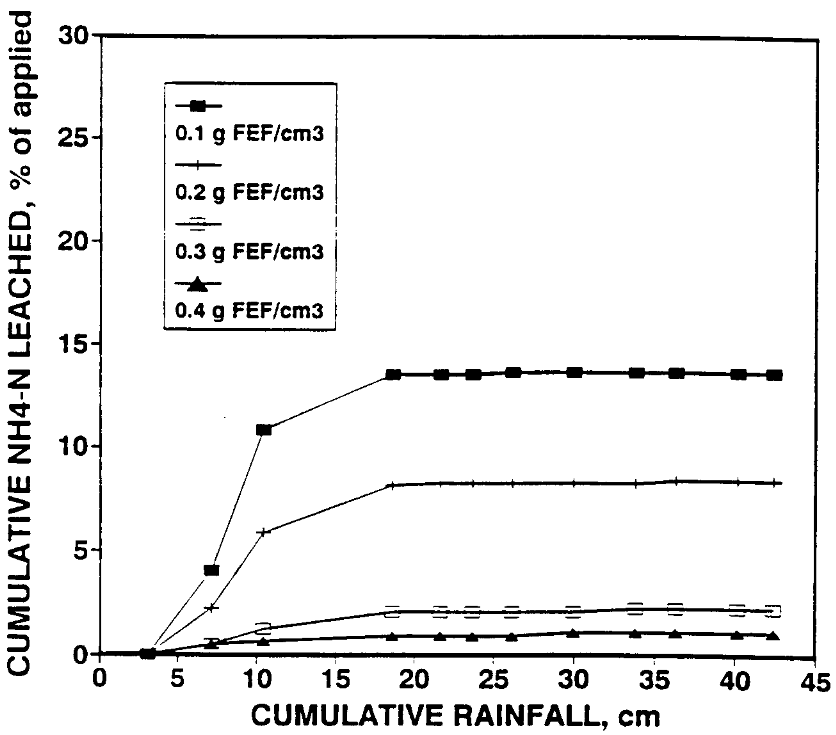

Fig. 3. Relationship between rainfall and the leaching of NH_4-N in Tropofolist soil as affected by the density of fines (<2 mm).

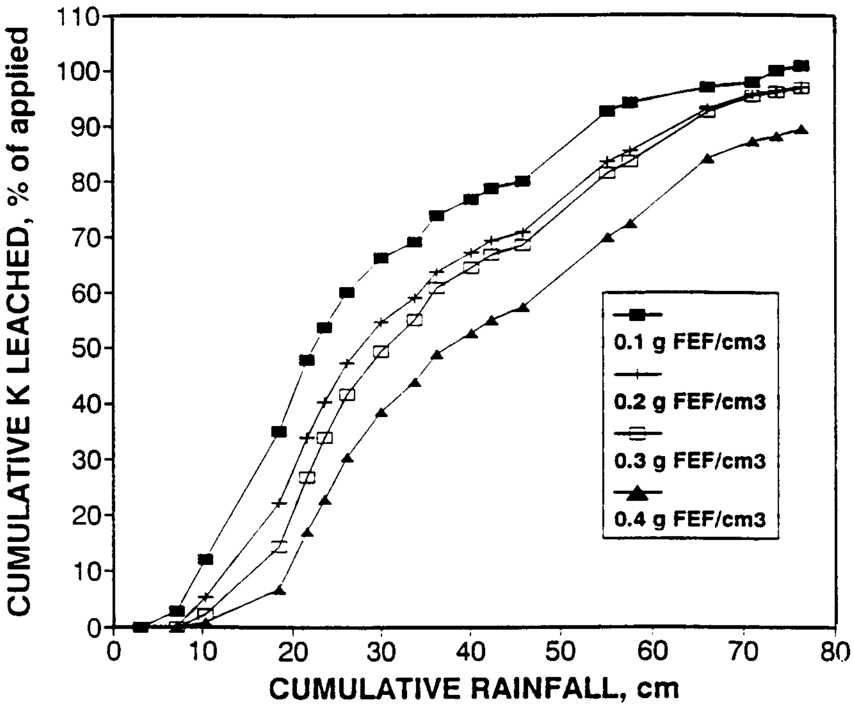

Fig. 4. Relationship between rainfall and the leaching of K applied to Tropofolist soil as affected by the density of fines (<2 mm).

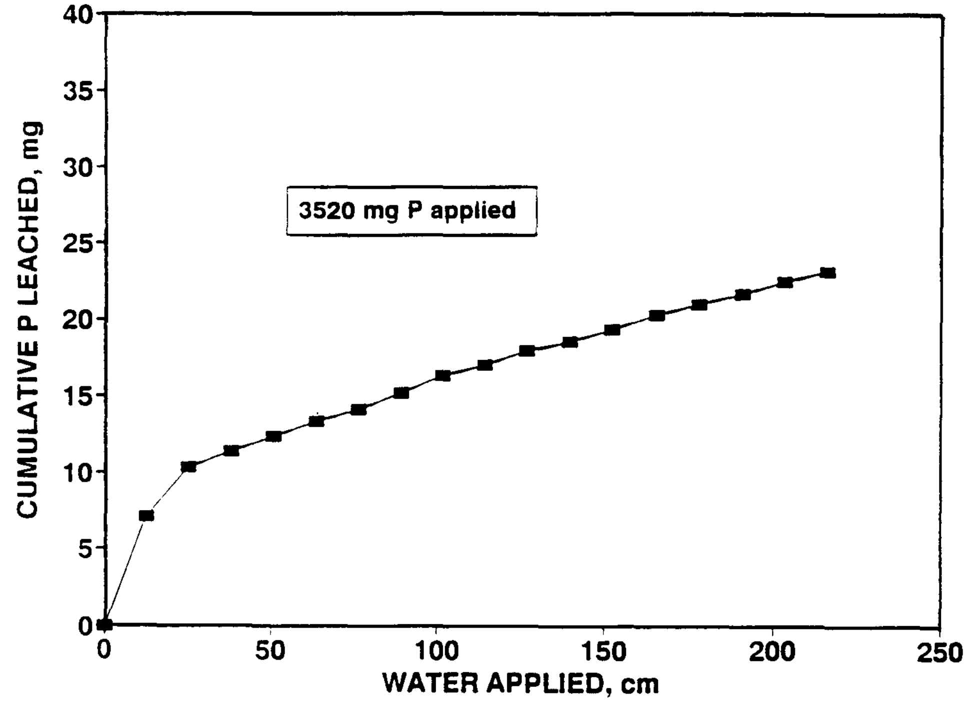

Fig. 5. Relationship between amount of water applied and the leaching of P applied to Tropofolist soil at the equivalent rate of 500 kg ha^{-1}.

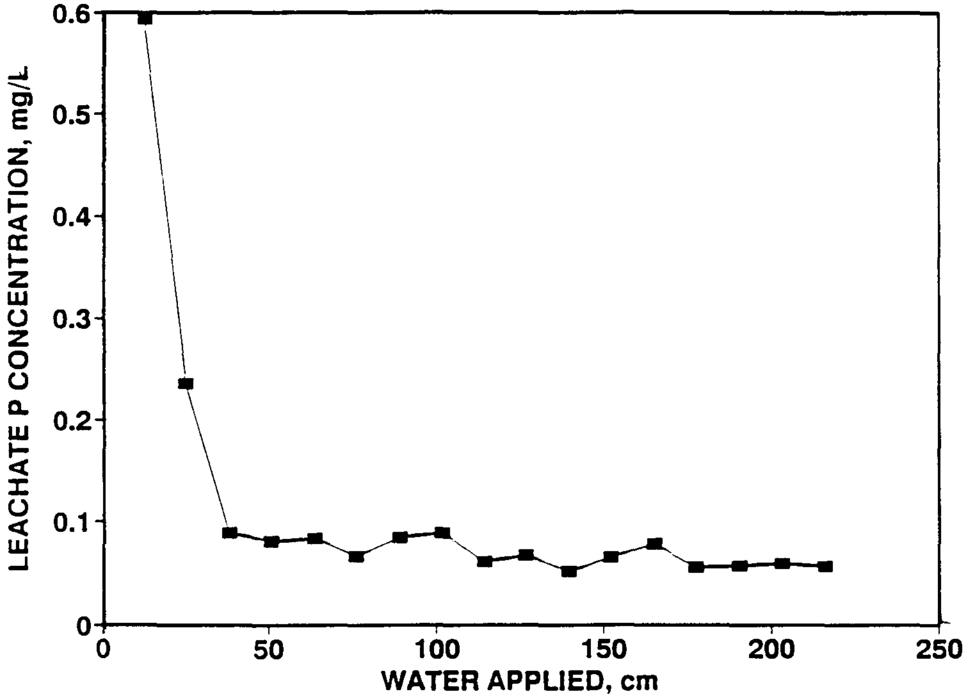

Fig. 6. Relationship between amount of water applied to a Tropofolist soil which received the equivalent of 500 kg P ha^{-1} and leachate P concentration.