Bioelement loss on clearing a tropical rain forest[*][1/]

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COMPENDIO

Se transformó un bosque lluvioso tropical con un capital de bioelementos conocido, en un barbecho con y sin quema y se registraron los cambios resultantes en las propiedades del suelo y en la reserva de nutrimentos.

El número restringido de réplicas y la gran variación local especialmente de la capa orgánica dentro del bosque, no permite dar más que un intervalo de las pérdidas de bioelementos infligidas al ecosistema forestal por tumba, quema y cultivos durante un año. Las pérdidas en los cationes intercambiables son del orden de 60-140 kg K/ha, 100-240 kg Ca/ha y 30-80 kg Mg/ha. Estas pérdidas pueden compensarse con la precipitación en rastrojos secundarios suficientemente vigorosos, sólo durante periodos de barbecho comparativamente largos (10-20 años).

Los 1300 a 1400 kg N/ha que se pierden en la vegetación y en el suelo (con distribución variable y relaciones C/N dependientes de los tratamientos), parecen ser más fácilmente compensados por tasas de fijación de 100 a 150 kg/ha/año. Estas últimas cifras se derivan de un estudio comparativo de algunos sitios de pastizales secundarios y barbechos con condiciones similares de suelo. — Los autores

Introduction

CLEAR-FELLING and burning of primary forests or secondary regrowth disrupts the mineral cycle and sets free sizeable quantities of bioelements, from both vegetation and soil, in volatile or dissolvable form. The former are lost from the site though some of it may return to the region with the rain. How much of the dissolvable bioelements are lost by leaching will depend on climatic and soil conditions and land use practices. At present, very few data exist on the bioelement stores of tropical primary and secondary vegetations (2, 13) and even less on the changes inflicted on soil bioelement stores during and after clearing though such data should be of vital interest for certain South American regions where the forest is presently cut at a formidable rate.

The data which the present paper is contributing, were obtained at a humid tropical lowland site of the Middle Magdalena Valley, Colombia, during a study of the bioelement stores of primary and secondary vegetation sites. The clear-felling of the forest in the experimental area provided the opportunity to examine the effect of burned and unburned clearing though this study had to adapt to the requirements of the primary study, especially in regard to the time interval and the number of samples to be analysed. Quantitative balances of bioelement changes in forest ecosystems suffer from the enormous short distance variation in the composition of the organic layer and soil. Therefore, our data cannot claim to supply more than approximated intervals of bioelement losses and rates of nitrogen fixation.

Materials and methods

The study area is situated on the Pleistocene terraces of the Magdalena. The terrace material constitutes a dense parent material on which 3000 mm of annual rainfall result in long phases of high water saturation with intervening irregular phases of drought. The sea-

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sonal evergreen forest on these acid terrace latosols is a low (max 30 m), two-layered stand with a considerable contribution of palms (7). Because of the high seasonal water saturation of the mineral soil, a great part of the fine roots grow on the surface forming a coherent root mat mixed with organic debris (F layer) (6), while root penetration into the soil is restricted to the uppermost 30 cm Wind fall of trees is common, and the ground surface is characterized by pits (hogwallows) Total biomass of the stand belongs to the lowest recorded in tropical evergreen forests (180 t/ha)

The experiments were planned as balances between total bioelement stores before and after cutting respectively cutting and burning of the vegetation The biomass and the different bioelement stores in the different plant compartments were estimated by means of allometric regressions based on data from harvest trees of selected dimensions and type. The size of the sample was 40 trees in the primary, and 23 trees in the older secondary forest Undergrowth and younger regrowth stages were harvested on plots of 10 x 10 to 4 x 4 m Plant components (leaves, twigs, branches, stemwood, palm fronds, etc) were analysed separately for dry weight and bioelement content For more details of method and results see the paper by Fölster, De las Salas, and Khanna (7).

The sampling of the organic layer and the soil was carried out on 10 x 10 m plots Six volume samples (20 x 20 cm) of the organic layer were taken per plot and combined to a composite sample Similarly, one composite soil sample was mixed per 10 cm depth layer, from 6 auger samples Because of the shallow rooting, only data from 0-50 cm depth have been included in the soil store In the original lay-out, two plots were planned as replica for each treatment However, the short distance variation, especially in the thickness of the organic layer, proved to be too great, in regard to some elements greater than the changes due to clearing. Therefore, each plot had to be balanced separately, and the final balances be treated as replica. This change intervened with our original lay-out with the result that the number of plots per treatment is uneven, and that two plots of the unburned fallow had to be balanced against one and the same forest plot

Soil and vegetation samples were analysed for bioelements in the Institut für Bodenkunde und Waldernährung, Göttingen In the organic layer, the total soil only in regard to N Ca-, Mg-, K stores in the soil were those exchangeable with ammonium-chloride at the pH of the soil Organic P, Al- and Fe-phosphates were determined in the soil besides total P The sum of the former have been used in the balance.

The spacial variation in soil bioelement stores requires to keep the unit area of study small The respective unit area for woodland biomass (and the bioelement store) determination is necessarily larger (1, 3, 14)

This discrepancy poses a methodical problem of correcting the overall figure for the bioelement store of the vegetation for every soil unit For this purpose, we assumed that woody matter would not loose bioelements at an appreciable rate within the first 6-12 months after clearing On the unburned fallow, stem wood was actually removed from the plots but the neglect of bioelement loss from twig wood implies a slight underestimation of total bioelement losses Results from the burned fallow show that the assumption was wrong here; the charring of twigs and tree bark contributed considerable amount of ash though the fire was not very hot This addition from wood charring could, however, be determined in the organic layer directly after burning In regard to leaf biomass, we corrected the overall figure (10 t/ha) by means of the added twig biomass on the ground surface of the plots (balance before and after clearing) and the twig: leaf ratio assuming that the amount of tree leaves and palm fronds would be inversely related The corrected leaf biomass (line two, Tables 2 and 3) does not deviate substantially from the overall figure.

Results and discussion

The unburned fallow

The total bioelement store and its distribution in the primary terrace forest is shown in Figure 1 The soil site is comparatively well supplied with nitrogen The N-content in the leaves is rather high (about 20 mg/g) Because of the low biomass of the forest, only 10 per cent of the total store is found in the vegetation The percentage figure for P in the vegetation does not even reach that level (6 per cent) From 50 to 80 per cent of the soil P occurs as occluded phosphates, and the P-content of leaves (0.7 - 1.0 mg/g) and wood (0.1 mg/g) belongs to the lowest recorded in tropical forest vegetations. The cations, on the other hand, show a high accessibility so that the very low soil reserves

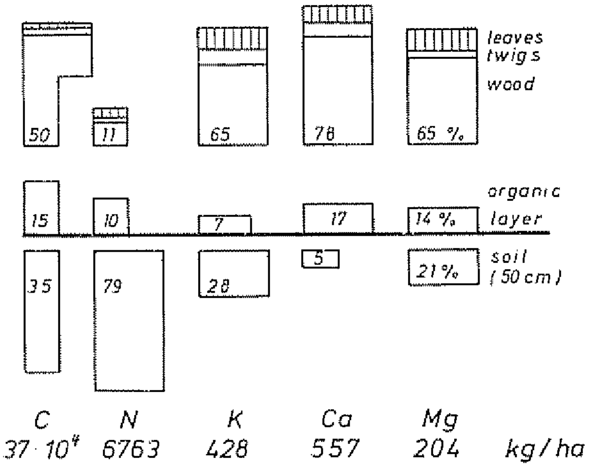

Fig 1 —*Total carbon and bioelement stores of the primary forest, and their per cent distribution between vegetation, organic layer and soil* have been mobilized to a considerable extent. Of the total stores, 50 - 70 per cent are contained in the above-ground vegetation, and of these, again 5 - 20 per cent return annually to the soil with the leaf litter. The K/Ca-ratio varies in leaves (1.08) and wood (0.77). In the organic layer, K is released at a fast, Ca and Mg at a much a slower rate (6), but the element content of the actual F-layer + root mat it low

The results of the clearing and of one year fallow without burning have been summarized in Table 1. The losses in and above the mineral soil have been balanced separately. Because of the required rearrangement, the two plots of the fallow are balanced against one and the same pre-clearing plot. The former have been placed in such a way as to overlap with the latter. The variation in the plot balances of the organic layers (Table 1, line 5) do not only reflect the existing spacial variation of the organic layer weights. Disturbances arise from the break-down of twig material which adds to the organic layer during the year of fallow, but also from the root tangle of the F-layer from which organic debris falls into the mineral soil during the sampling procedure, especially when thicker living roots pass through the sampling area and have to be cut. This was the case in the second plot (Table 1) where a great loss of C in the organic layer is partly compensated by a gain in the uppermost 10 cm of the mineral soil. Analytically, this gain is obvious but cannot be calculated because of the simultaneous loss of soil humus. The remaining variance of the total loss balance is still unsatisfactorily high.

The data of Table 1 imply that wood (twigs, branches, trunks) does not loose any bioelements during one year. This assumption certainly underrates the possible speed of wood decay so that the losses of Table 1 represent minimum figures. However, the low C/N-ratio (C/N = 7) of the carbon and nitrogen losses indicate that it is easily decomposable organic matter that constitutes the bulk of the organic matter loss. During the decomposition of this material Ca, Mg and K have been mineralized and been leached beyond the rooting limit level with the cations added with the leaf biomass.

The burned fallow

Three plots were sampled before clearing, immediately after burning the slash (before the first rain), and again after 5 months when the experiment had to be discontinued.

The changes before and after burning concerned the organic layer only and provided information on the amount of volatile loss, as well as on the extent to which elements accumulated from material not accounted for in the input (Table 2, line 3). Such additional salt naturally stems from the burning of wood. The actual

Table 1.—Balance of bioelement store in forest and unburned fallow (2 plots).

	t/ha		kg/ha									
	org C		N		P		K		Ca		Mg	
1) Organic layer before clearing	15		394		19		24		163		33	
2) Leaf biomass added through clearing	6		227		9		67		56		25	
3) Input	21		627		28		91		219		58	
4) Organic layer one year after clearing	20	8	612	230	21	8	36	18	183	97	43	22
5) Minimum loss above mineral soil	—1	—12	— 15	— 597	— 7	—20	—55	—73	—36	—122	—15	—36
6) Loss in mineral soil (0-50 cm) during one year fallow	—6	+ 2	—1116	— 864	—17	+ 8	+27	—13	+10	+ 33	+ 2	— 2
7) Total loss	—7	—11	—1131	—1461	—24	—12	—28	—86	—26	— 89	—13	—38
— separate for both plots	C/N = 6—8											
— average	—9		—1296		—18		—57		—58		—26	
	C/N = 7											
— % of forest store			—19,2 %				—13,3%		—10,5%		—12,7%	

Table 2.—Balance of bioelement store in forest and burned fallow (3 plots).

	t/ha			kg/ha														
	org. C			N			P			K			Ca			Mg		
1) Organic layer before clearing	14	21	62	197	656	1513	8	12	35	21	29	56	86	49	88	21	24	35
2) Leaf biomass added through clearing	6	5	6	227	190	213	9	9	9	67	60	63	56	40	52	25	20	23
3) Input (min.)	20	26	68	424	846	1726	17	21	44	88	89	119	142	89	140	46	44	58
4) Organic layer immediately after burning	10	10	20	190	202	580	23	25	30	85	105	70	276	288	276	76	77	57
5) Volatile loss	—10	—16	—48	—234	— 644	—1140												
6) Addition from wood + bark							+ 6	+ 4	—14	— 3	+ 16	— 49	+134	+200	+136	+30	+33	— 1
7) Organic layer 5 month after burning	10	10	20	242	191	516	7	6	12	9	5	14	111	75	83	26	16	19
	C/N = 44																	
8) Loss against 4	—	—	—	+ 52	— 11	— 64	—17	—19	—18	—76	—100	— 56	—165	—213	—193	—50	—61	—38
9) Change in mineral soil (0-50 cm) during 5 months fallow	—14	(—24)	— 6	—384	(—1470)	+ 85	—21	+14	—17	+70	+ 99	+ 90	+ 34	+151	+ 91	+29	+62	+95
10) Total loss																		
— separate for 3 plots	—24	(—40)	—54	—556	(—2125)	—1119	—38	— 5	—35	— 6	— 1	+ 34	—131	— 62	—102	—21	+ 1	+57
— average	—39			—838			—23			+ 9			— 98			+12		
	C/N = 46																	
— % of forest store				—12,4 %									— 17,8 %					

amount burned probably does not make up a sizeable portion of the existing store of the clearing but much of it was charred on the surface. The bark is richer in bioelements than wood and has a much lower K/Ca-ratio (15, 18). This might explain why Ca and Mg dominate the excess salt.

How much woody matter was lost due to burning could not be determined. The volatile loss of line 5 (Table 2) is, therefore, a minimum figure. The organic layer has been strongly affected, not only the L-layer (3 - 6 t/ha) but also the F-layer. The loss increases with the thickness of the organic layer from about 10 per cent to almost 70 per cent in the plot with highest organic matter accumulation in the forest (120 t/ha). The C/N ratio of the volatile loss is slightly higher than that of the organic layer (36/31).

After five months, i.e. after the first part of the rain maximum, the quantitative changes in the organic layer were negligible, obviously because less easily decomposable material (C/N = 44) had remained after burning. However, the rain of the 5 months effectuated a transfer of P to the mineral soil, and a complete (K) or considerable though incomplete (Ca, Mg) leaching of cations from the organic layer, but not yet from the rooting zone of the mineral soil. Figure 2 shows the vertical distribution of cations in the mineral soil at this time in comparison to the original situation (forest) and the situation under the unburned fallow one year after clearing. It seems that the first flush of easily dissolvable cations had already been washed down (probably following the early rain maximum of the first 2½ months (March/May: 1090 mm) after the burning) to a depth of 40 - 50 cm (K, Mg), in the case of Ca also beyond. Ca is the only element with a marked negative balance. Leaching later slowed down, probably following the rains (June/July: 240 mm), the decreasing availability of HCO_3^- and the decreasing ion concentration. The total loss of cations in Table 1 and 2 show little difference, and this is statistically uncertain because of the great variation of plot results and plot conditions, but also because of the different time length involved.

The store of "available" phosphorus (org., Al- and Fe-phosphates) decreases in both treatments by about 20 kg/ha, that of total P by about 8 kg/ha. As leaching of P needs not to be considered, these figures may indicate some change in the solubility of P-compounds.

In regard to nitrogen and carbon, the total balance figures demonstrate that the fire also attacks less easily decomposable organic matter. The C/N ratio of this loss (C/N = 46) is much wider than in case of the unburned plots (C/N = 8) so that actual N-losses are smaller than on the unburned plots (12 as against 19 per cent of the original N-store of the ecosystem). In case of the burned plot, 75 per cent of the N was lost below the mineral soil surface, mainly in the top soil (0 - 20 cm). In case of the burned plots, this relation was reverse. The C- and N-data of the soil balance of the second plot have not been considered

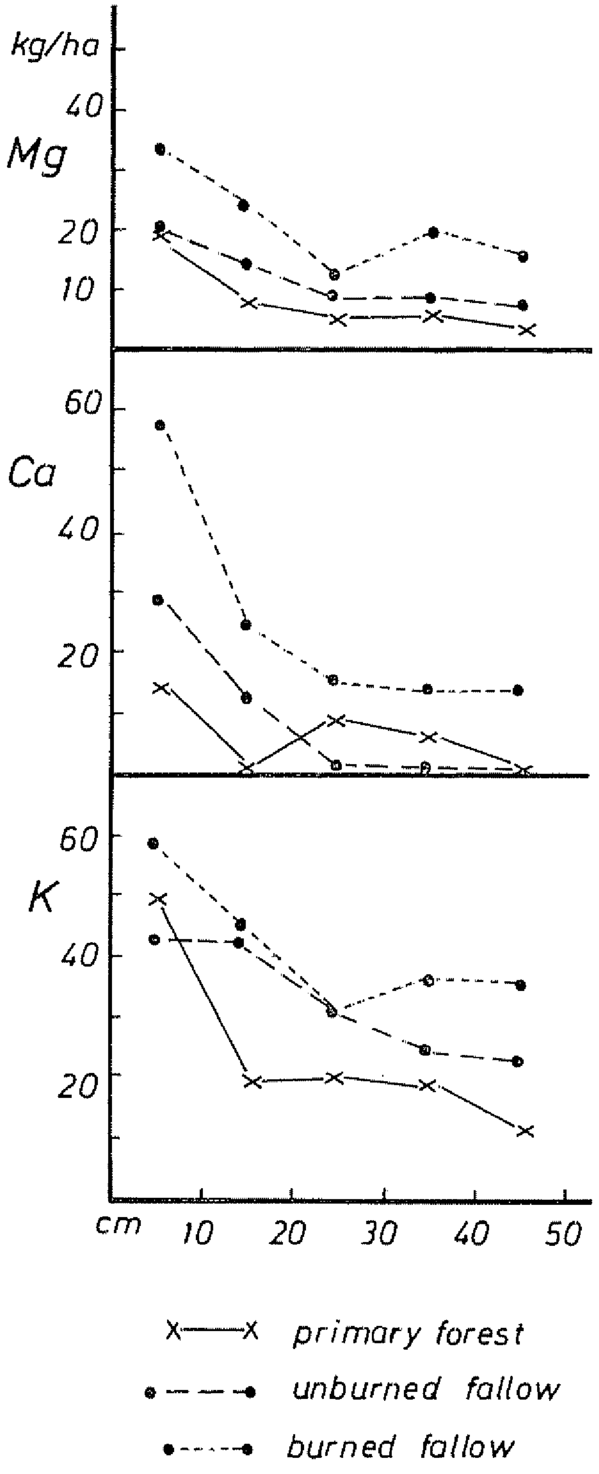

Fig. 2.—*Vertical distribution of cation stores in the soil of primary forest, unburned and burned fallow.*

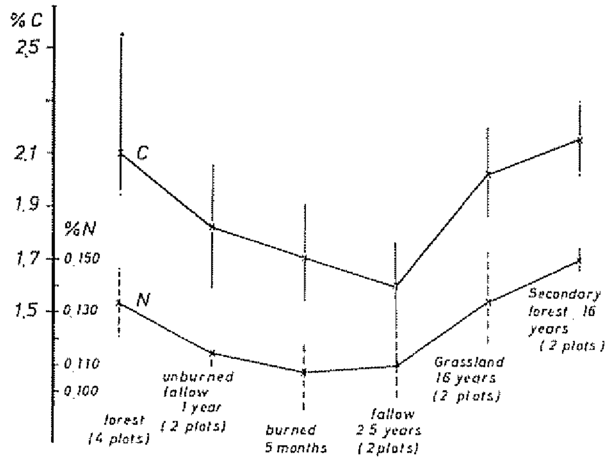

Fig 3.—*Changes in C and N per cent in the uppermost 10 cm of the soil following different clearing treatments and under secondary vegetation*

(brackets) as the forest plot had exceptionally high C-contents in the subsoil. The most likely explanation is that one or two of the auger holes hit a subsoil disturbance which can develop in connection with tree fall Apart from this exception, the changes in the mineral soil occur mainly in the surface layer, for which C- and N-contents have been summarized separately in Figure 3. The drop from the original to the actual contents in the soil of the fallows amounts to about 15 per cent A similar decomposition constant was found by Cunningham (4).

Figure 3 also includes data from two plots of an older fallow in the immediate environment of the clearings The site had been cleared, burned and cultivated with upland rice before it was abandonned to natural regrowth which, after two years, had built up a biomass of 19 t/ha Because of the more severe burning and the cultivation, the soil humus had been affected more strongly, though accretion especially from grass litter has certainly lifted the present figures above their absolute minimum after cultivation. If the bioelement stores of the primary forest are compared with those of the 2 years fallow, the difference would suggest a total loss of 1800 kg N, 200 kg K, 380 kg Ca and 120 kg Mg These figures include the bioelements of the wood, and are, therefore, certainly too high as some of the wood was still present on the fallow, and because some of its bioelements would be taken up by the gradually developing root system of the fallow.

In order to arrive at a reasonable estimate of bioelement losses after forest clearing and one year of burned and cultivated fallow under the humid tropical conditions of the Magdalena valley, one can only envisage an interval range that takes into account the variable combinations of treatment and meteorological conditions. As lower limit, we suggest the losses of our unburned plots increased in regard to C and Ca because of the additional fire The above mentioned difference between the stores of the primary forest and the 2 years fallow could be used as upper limit though after subtracting 50 per cent of the cations and 100 per cent of the C and N contained in the wood The interval thus obtained (Table 3) appears to approach a reasonable average though the N values may be somewhat closer.

Recovery of bioelement losses

The bioelement losses inflicted on the ecosystem during or because of human interference involve an appreciable portion of the original bioelement store of the ecosystem (15 - 45 per cent, see Table 3). One has to bear in mind, that the high rainfall and the sudden death of 200 t of vegetable matter represent the most favourable conditions for great bioelement losses, and that these decrease markedly in adapted shifting cultivation systems with shorter fallow cycles and narrower fluctuations of the soil organic matter (13). On the other hand these singular losses are definite and not

Table 3.—Bioelement loss on clearing of a rain forest (in brackets: per cent of total store), average annual bioelement input with the rainfall, and their quotient, i.e the number of years needed for recovery of the loss, by rainfall input.

Bioelements	t/ha	kg/ha			
	org C	N	K	Ca	Mg
Loss minimum	40 (11)	1300 (19)	60 (14)	100 (18)	30 (15)
Loss maximum	60 (16)	1400 (21)	140 (33)	240 (43)	80 (39)
Input with rain	—	15	7	5	3
Bioelement loss / Input with rain (min)	—	86	9	20	10
(max)	—	94	20	48	27

recoverable. On a regional basis, some of the volatile loss including ash particles that were blown up into the air, may return to the ground. They add to the bioelements contained in the rain from other sources and —together with nitrogen fixed from the atmosphere— constitute the only possible accretions to the bioelement store of the soil.

No data concerning the element content of the rainfall are available for the Magdalena valley. We, therefore, used an average of the not very numerous data available for the tropics (13, 16, 19) and juxtaposed this possible annual accretion to the site with the proposed loss figures in Table 3. The comparison shows that the elements contained in the rain could not possibly play any role in land use systems with brief fallow periods. The longer the life span of a fallow, the more important the size of this accretion, at least under the assumption that the developing root system of the fallow will be able to retain most of the added bioelements and keep them circulating in the secondary regrowth. Cations may then be accumulated in quantities equivalent to the minimum losses in Table 3 when the fallow is allowed to grow for 10 (K, Mg) or 20 (Ca) years. The assumption of a loss-free bioelement cycle can, of course, not be maintained. Otherwise, the primary forest would be rich in bioelements. However, the annual loss of the circulating bioelement stock will vary with the element concentration of the circulating solutions. In mature forests, one can assume an equilibrium between leaching output and addition with the rain to be maintained (11). In the fast growing stages of the secondary regrowth, high annual rates of bioelement fixation in the vegetation maintain a disequilibrium in the bioelement flow which might support high uptake rates from the bioelements in the rain, without which it would, in fact, be difficult to understand the subsistance of centuries old shifting cultivation systems.

In regard to nitrogen, the ratio between loss rate and the content in rain water is less favourable, and the number of years required to compensate the loss from rainfall addition 5 to 10 times higher than for the cations. Irrespectively, the secondary regrowth builds up a nitrogen store in the aboveground biomass. Following the figures given by Nye and Greenland (12) for N-stores in tropical secondary vegetations, the annual increase of the above-ground N-store amounts to 25 - 75 kg N/ha/yr. The simultaneous increase of soil humus normally accompanying this development suggests N-fixation as source.

In the Magdalena valley, we studied three regrowth stages of similar species composition and different age (2,5 and 16 years) (7). In this case, the above-ground N-store (vegetation and organic layer) increased from 276 to 609 and to 1045 kg respectively. Soil nitrogen increased also but we don't know the original humus content of the soil before and after clearing and burning. The soil sites of the 2 years and the 16 years regrowth were practically identical with that of our forest and fallow site so that we included figures of the 16 years regrowth site, as well as of a neighbouring grassland site, into Figure 3, to show the possible extent of C- and N-regeneration in the surface layer of the soil. In order to arrive at a quantitative estimate of the actual N-fixation under secondary regrowth we again propose a range interval between minimum and maximum values:

- Minimum estimate: Assuming the soil organic matter to have remained unaltered since the clearing, the above-ground N-store of the 16 years regrowth would imply an average annual fixation of 50 kg/ha/yr — in case of the 2 years fallow (and without considering the organic layer which still contains residues of the forest) the rate would be 75 kg/ha/yr, and 55 kg/ha/yr in the 5 years regrowth.
- Maximum estimate: Assuming that the difference in soil humus between the 2 years regrowth and the 16 years regrowth is due to humus regeneration, the annual fixation rate would amount to 160 kg/ha/yr.

One could also use the humus content of the grassland (see Fig. 3) as base to calculate the humus regeneration in the 16 years regrowth, as both belonged to the same clearing, and as one can be reasonably certain, that the rather well kept grassland did not lower but rather increase the lowest level of soil humus 1 or 2 years after the clearing and burning. The difference between the two N-stores would imply 100 kg/ha of annual fixation which can be considered the more likely minimum estimate, though variations with age and quality of the regrowth may be expected. More exact information would require many more regrowth sites to be studied, which would be desirable also in regard to the suggested regeneration of the cation stores.

Moore (12) and Ruinen (17) have summarized some estimates of annual N fixation in tropical grassland and forest systems. Our proposed range of 100 to 150 kg/ha/yr of fixed nitrogen does not reach the high level of 650 kg/ha/yr found by Jaiyebo and Moore (10), but is higher than most data from forest systems while equivalent levels have been reported from grasslands. Greenland and Nye (9) suggested fixation rates between 50 and 150 kg/ha/yr. Most of this gain can be expected to have derived from non-symbiotic fixation. They are, however, net gains without the leached and volatilized accretions. Gross fixation according to Ruinen (17) might well be 2 to 3 times higher, while Nye and Greenland (13) do not consider high N-losses likely in the dense fallow vegetation.

Summary

A tropical rain forest of known bioelement store was turned into unburned and burned fallow, and the resultant changes in soil properties and element store were determined.

Restricted number of replica and great local variation especially of the organic layer within the forest do not permit to give more than a range interval of bioelement losses inflicted on the forest ecosystem due to

clearing, burning, and cultivation for one year: Cation losses in the order of 60 - 140 kg K, 100 - 240 kg Ca, and 30 - 80 kg Mg are possible and can be restored by rainfall input in sufficiently vital secondary regrowth only during comparatively long fallow periods (10 - 20 years) The 1300 - 1400 kg N which are lost above and below ground (with varying distribution and C/N-ratios depending on the treatment) appears to be more easily restored by N-fixation rates of 100 - 150 kg/ha/yr The latter figures are derived from a comparative study of some secondary grassland and fallow sites of similar soil conditions

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