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Roots and the stability of forested slopes

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Abstract. Root decay after timber cutting can lead to slope failure. In situ measurements of soil with tree roots showed that soil strength increased linearly as root biomass increased. Forests clear-felled 3 years earlier contained about one-third of the root biomass of old-growth forests. Nearly all of the roots < 2 mm in diameter were gone from 7-year-old logged areas while about 30 percent of the < 17 mm fraction was found. Extensive brushfields occupied areas logged 12 to 24 years earlier. The biomass of brushfield roots < 2 mm in diameter was 80 percent of that in the uncut forest, and fewer large roots were found there than in the forest. Roots < 17 mm in diameter in the brushfield accounted for 30 percent of that found in the forest, and for total root biomass, only 10 percent. Individual, live brush roots were twice as strong as conifer roots of the same size. This difference may partially compensate for reduced root biomass in brushfields. Net strength of the soil-root matrix in brushfields was about 70 percent of that in uncut forests. If soils are barely stable with a forest cover, the loss of root strength following clear-felling can seriously affect slope stability.

Racines et la stabilité des pentes boisées

Résumé. La Pourriture des racines aprés coupe peut aboutir à des glissements de terrain. La mesure faite *in situ* du sol contenant des racines

d'arbre a révélé que la résistance du sol a augment& d'une facon linéaire à mesure que la biomasse racinaire a augment&. Les for&s exploitées trois ans avant contenaient environ les deux tiers de la biomasse racinaire qui se trouvait dans le vieux bois. Presque toutes les racines à < 2 mm de diamètre avaient disparu dans les terrains exploites sept ans avant taudisque à peu près 30 pour-cent de la fraction de < 17 mm s'y trouvaient. De vastes surfaces couvertes de buissons remplissaient les zones exploit&es de 12 à 24 ans avant. La biomasse des racines de buisson à < 2 mm de diamètre était 80 pour-cent de celle de la forêt non-exploit&e. Et moins de grandes racines s'y trouvaient que dans la forêt. Les racines à < 17 mm de diamètre dans les terrains buissonneux comprenaient 30 pour-cent de la biomasse trouvée dans la forêt, et de la biomasse racinaire totale, seulement 10 pour-cent. Les racines de buisson vivantes individuelles étaient deux fois plus résistantes que celles des conifères de la même taille. Cette différence peut en partie compenser pour la réduction de la biomasse racinaire dans les terrains buissonneux. La rhistance nette de la matrice sol-racine dans les terrains buissonneux était environ 70 pour-cent de celle des forêts non-exploit&es. Si le sol est à peine stable avant l'exploitation forestiere, la perte de résistance racinaire suivant l'exploitation peut produire des effets graves sur la stabilité d'une pente.

INTRODUCTION

Pacific rim steeplands contain some of the world's most unstable landscape together with much of its most productive forests. Little is known about the interaction of timber harvesting and mass erosion. Slides occur more often on slopes where the forest has been removed than where it remains. Root systems of plants can increase stability of forested slopes by anchoring through the soil mass into fractures in bedrock, by crossing zones of weakness to more stable soil, and by providing interlocking long fiberous binders within the weak soil mass. In deep soil, the vertical anchoring effect of roots becomes negligible, and the other two conditions predominate. After a forest is removed by fire or harvest, the root system decays and the soil progressively weakens. If the forest slope is marginally stable, landslide frequency often increases after trees are removed. As deforested areas revegetate, the soil mantle is again progressively reinforced as new roots occupy the soil.

IN SITU SHEAR STRENGTH OF FOREST SOILS

The strength of forest soils is difficult to measure directly, Standard equipment, such as the vane-cone penetrometer, is inadequate to measure this strength (Golob and Silversides, 1978), let alone the effect of roots on soil strength. Various measures of soil and root strength have been devised. Endo and Tsuruta (1969) developed a shear box to measure the contribution of small Alnus glutinosa roots to the strength of relatively homogeneous nursery soil. O'Loughlin (1972) used a modified design to study old-growth forests of coastal British Columbia, Canada. Both types of shear box enclose a block of soil which is sheared along the bottom as the box is moved. O'Loughlin found many roots larger than 5 mm in diameter pulled out of the soil block instead of failing along the shear plane. Endo and Tsuruta found that even roots 1 to 2 mm in diameter pulled from the soil blocks. How much roots contribute to the strength of soil can be underestimated if they are pulled from the soil block rather than break. Consequently, I have developed a shear box that shears a soil block along two parallel vertical planes. The shear box encloses the soil block, but remains open on two sides. The inside dimensions of the shear box are 60 cm wide, 30 cm long, and 30 cm high. Each open side is 30 cm square.

The box was field tested in the relatively simple soil-root system of a mature _Pinus contorta_ stand growing on coastal sands in northern California. At each test site, the front of the soil block to be sheared was carefully excavated. A sharpened *steel* plate was then pressed into the soil under the block, and the back of the soil block was excavated. Steel plates covering the top, bottom, front and back of the soil block were then bolted together. Stress was applied to the box by a mechanical jack extended at a rate of 1.27 cm/min for about 7 minutes. Stress was measured by using a proving ring mounted between the jack and the shear box. The proving ring reading was recorded every few seconds, and force over time was plotted. The maximum force *was* considered to represent the force required to shear the soil block. At three sites, the roots and soil within the shear plane were cut with a knife before the test, and the force required to move the box and soil block was measured. This force was considered to be the sliding friction. The shear strength of the soil block was calculated as the maximum force less the mean sliding friction.

The soil block was then carefully dissected, and detailed information on the position of stones and roots in and adjacent to the two side shear zones was recorded. Roots which are cut by the shear box, but which extend undisturbed in one direction, would provide strength to the soil block similar to that reported by Endo and Tsuruta (1969) and O'Loughlin (1972). These roots may pull out of the soil or they may break. However, roots lying horizontally and aligned about normal to the shear planes can continue undisturbed through the soil block and into the soil on either side of the shear box. These roots could not pull out of the soil block without breaking.

Soil samples were examined for particle size, bulk density, aggregate stability, and soil moisture. After the soil block was sieved, all roots were extracted, washed, separated into live and dead fractions, subdivided into six size classes, dried at 70°C, and weighed. From each test location, data were collected for 24 soil and root variables. Several classes were combined, adding an additional eight variables.

Endo and Tsuruta (1969) measured in situ the shear strength of cultivated nursery soil densely planted with Alnus glutinosa saplings which had an average stem diameter of 16 mm. They reported 53 per cent of the variation in soil "cohesion" was explained by the fresh weight of roots.

O'Loughlin (1972) evaluated the influence of six soil variables and one root variable on the in situ shear strength of glacial till subsoils in a mixed old-growth Pseudotsuga menziesii, Thuja plicata, and Tsuga heterophylla forest. The fresh weight of roots was the most significant of the variables, accounting for 56 per cent of the variation in soil strength. The fresh weight of roots in the soil samples averaged 2.51 kg/m^3 -- about one-third of that reported by Endo and Tsuruta.

Most forest biomass studies report oven-dry weight rather than fresh weight. I found the dry weight of roots predicted soil. shear strength about as well as the fresh weight of roots.

To understand which variables are most useful in predicting the force required to shear the soil block, I screened the 32 variables by using all possible subsets regression and partial F-tests. The "best" regression equation contained only a single variable -- the dry weight of live roots < 17 mm in diameter (Fig. 1):

$$\text{Strength} = 3.13 + 3.31 \text{ Biomass},$$

in which strength is in kPa and biomass in kg/m^3. The equation explains 79 per cent of the variation in strength ($r^2 = 0.79$, $n = 18$) and is statistically significant at the 1 per cent level ($F_{1,16} = 56.8$). The mean biomass of the < 17 mm live roots was 1.77 kg/m^3, which represents 64 per cent of the total root biomass. Adding more variables did not significantly improve the regression equation.

The squared correlation coefficient between the force required to shear the soil block and the dry weight of live roots in the soil block helps identify the ability of different root size-class groupings to predict soil strength (Table 1). The best relationship was between soil strength and the biomass of live roots < 17 mm in diameter. Since Endo and Tsuruta (1969) and O'Loughlin (1972) used the total fresh root weight, the explained variance of their equations might also have been improved if other size classes of roots and a distinction between live and dead roots had been used.

In old-growth forests, I found many more horizontal roots than vertical roots, My equation probably underestimates the true soil-strengthening effect by roots because roots oriented vertically and parallel to the axis of movement of the shear box were cut by the front, back, and bottom plates of the box. I did not measure the orientation of the roots, but would estimate that the root effect is underestimated by at least one-half.

ROOT BIOMASS

The studies that have directly measured the *in situ* strength of soil which contains tree roots have all identified the weight of roots in the sample as the principal variable related to measured strength. O'Loughlin (1972) calculated that the root network accounted for 71 per cent of shear strength at saturation of the till soils he studied on slopes of 35 degrees. Bjorkhem et al. (1975) observed that the imposed load may be 70 per cent greater before soil-rupture in soils with a root network than in soils without roots.

Slope stability problems could easily develop as the tree root system decays after timber cutting on steep slopes. Little is known, however, about changes in root biomass after timber harvest and subsequent revegetation. To study these changes in root biomass, an area was selected at 1300 m elevation in the Klamath Mountains of northwestern California. The soil is a gravely fine sandy loam derived from deeply weathered diorite. The vegetative community is the white fir phase of the mixed conifer forest. *Abies concolor* dominates the old-growth forest, but variable combinations of *Pseudotsuga menziesii*, *Pinus ponderosa*, *Pinus lambertiana*, and *Libocedrus decurrens* are found in the coniferous component and *Arbutus menziesii* and *Castanopsis chrysophylla* in the hardwood component. When the forest is opened by fire or logging, extensive brushfields, composed principally of *Ceanothus velutinus*, commonly occupy the openings for several decades. Even with site preparation and conifer planting, the brush has not been controlled successfully in the study area.

Roots were extracted from 400 soil cores collected from areas that had been clear-felled up to 24 years earlier. Each core contained about

3200 cc of soil. The variances within and between areas were so large that no trends in root biomass with time after logging could be detected. The two most obvious ways to reduce the variance are to increase either the volume of individual samples or the number of samples. The number of samples required to determine a trend in biomass related to time after logging was calculated to be in the tens of thousands. And so the size of each sample was increased about 400 times to a volume of 1 1/3 m^3.

A block of soil 1 m square was excavated to a depth of 1 1/3 m in 1/3-m increments. The soil was screened and roots were extracted, separated into live and dead components, washed, sorted into six size classes, dried at 70°C, and weighed. Only a few roots were found below a depth of 1 m. Roots were taken from 103 soil blocks representing six different ages of cutblocks up to 24 years and an uncut old-growth stand. For convenience, the following discussion will refer to changes over time, even though data came from different areas. This is probably permissible because care was taken to select areas physically close to one another which had the same soil type and depth, slope, aspect, elevation, and forest density. Within each of the seven study areas, about six soil blocks were clustered around each of about three randomly selected l-m by 2-m access pits. The mean root biomass for each of the size classes was calculated by using cluster sampling formulae (Fig. 2).

The 3-year-old cutblock supported an extensive cover of bracken fern (Pteridium aquilinum). Through decay, root biomass decreased to about two-thirds of that found in the uncut forest. The proportion of the roots which had decayed decreases as the size of the roots increases. Live Pteridium roots (rhizomes) returned to the cutblock about 10 per cent of the live root biomass found in the uncut forest for < 17-mm roots.

Within 7 years after logging, *Pteridium* had been replaced by widely scattered brush and herbaceous species. The live root biomass dropped to about 3 per cent of that in the uncut forest. The dead root component continued to decline as decay progressed. Essentially all of the < 2-mm roots had decayed within 7 years; about 30 per cent of the < 17-mm dead roots remained.

Within 12 years after logging, the cutblocks had revegetated with *Ceanothus velutinus* rather than conifer regeneration, The brushfields occupied all cutblocks that had been logged 12 to 24 years earlier. The biomass of small live roots increased dramatically in these brushfields. Within 12 years after cutting, live roots < 2 mm in diameter had recovered to 82 per cent of that in the uncut forest. Live root biomass of larger roots, however, recovered more slowly. The biomass of live roots < 17 mm in diameter was about 30 per cent of that of the uncut forest, while total live root biomass in the brushfields was only about 10 per cent of that in the forest. Virtually all but the largest of the roots which were alive before harvest had now decayed. Generally, all that remained of the dead roots were shells of bark surrounding completely decayed wood. Occasional sound resinous dead roots were found in all logged areas -- similar to results reported by Ziemer and Swanston (1977) in southeast Alaska. Such decay-resistant resinous roots accounted for, perhaps, less than 5 per cent of the total forest root biomass in the northern California study. As non-resinous roots decay, however, the resinous root fraction becomes the dominant component of residual root biomass.

STRENGTH OF INDIVIDUAL ROOTS

Although roots generally tend to break in tension rather than shear during slope failure, root shear strength is much easier to measure and allows the study of larger roots than is allowed by tensile strength apparatus. Measurements of root tensile strength reported in the literature have been limited to root diameters less than 15 mm, and most studies have been conducted on roots smaller than 4 mm in diameter.

I recently developed a direct shear apparatus which satisfactorily measures the shear strength of individual roots up to 50 mm in diameter (Ziemer, 1978). Shear strength measured by this apparatus was closely related to tensile strength measured by an apparatus developed by Burroughs and Thomas (1977):

$$\text{Tensile strength} = 75 + 2.2 \text{ Shear strength},$$

in which strength is expressed in newtons. The explained variance (r^2) was 0.97. No difference by species in the relationship was detected. These results suggest that direct shear measurements can be used as a surrogate of root tensile strength.

The strength of roots varies between tree species (Turmanina, 1965; O'Loughlin, 1972; Ziemer and Swanston, 1977). Segments of roots were collected from the northern California root biomass study area for each of the nine principal tree and brush species (Table 2). For each species, approximately 10 roots were collected for each of six size classes, ranging from 2 to 50 mm in diameter. Each root was sheared about five times (Ziemer and Swanston, 1977; Ziemer, 1978).

A least-squares regression of log shear strength over log root diameter yielded excellent results for each species. The explained variances for the nine equations ranged from 0.93 to 0.99. Shear strength was then calculated for each of the six root diameters. The species were ranked by decreasing root shear strength for each root diameter, then by decreasing rank averages over all diameter classes (Table 2). On the basis of Kendall's coefficient of concordance (Kendall, 1975), the ranks within each diameter class agree in the overall order of the species at the 1 per cent level of statistical significance.

As diameter increased, the species generally maintained their relative position in the ranking. Two species shifted in rank, however, as diameter increased. *Arbutus* had the weakest 2-mm roots, but its relative rank markedly changed as size of roots increased, and its large roots were among the strongest. *Libocedrus,* in contrast, had the strongest 2-mm roots, but its large roots were among the weakest.

The shrub and hardwood species have stronger roots than conifers. *Ceanothus* roots, a major component of brushfields, are about twice as strong, on the average, as *Abies* and *Pinus* roots. *Ceanothus* roots 2 mm in diameter are about 1.35 times as strong as the conifer roots. Their biomass was about 82 per cent of that in the forest. The difference in strength more than compensates for the lower biomass. The contribution of these small roots to the strength of the soil is estimated to be about 10 per cent greater in the brushfield than in the forest (i.e., 1.35 times 0.82). Brush roots 17-mm in diameter are about 2.13 times stronger than fir and pine roots, but their biomass is only 32 per cent of that of the forest. And their relative contribution to soil strength would be about 68 per cent of that of the forest. The 50-mm diameter brush roots are about 3.76 times stronger than fir and pine roots, but these brush roots account for only 4 per cent of the root biomass of this size class found in the forest.

ESTIMATED TRENDS IN SLOPE STRENGTH

Roots < 17 mm in diameter are most useful in calculating relative changes in slope strength because the biomass of that size class was the best predictor of *in situ* shear strength. As roots decay they lose both biomass and strength. Root strength loss can be conservatively assumed to be proportional to root biomass loss. For a given biomass, the strengthening effect of dead roots on the soil-root matrix is assumed to be equal to that of live roots. Relative reinforcement of the soil by roots was computed by summing over size/species classes the products formed by multiplying the relative root strength by the proportion of root biomass for each class (Fig. 3).

The dead root component in all study areas was predominately conifer roots. The relative reinforcement by dead roots follows an exponential decline with time after logging (Fig. 3). About half of the original reinforcement was gone within 2 to 3 years after logging. Three-fourths of the strength was lost within 8 years. Essentially all of the reinforcement by dead roots was gone within 25 years after logging.

The pattern of the relative reinforcement by live roots follows a more complicated pattern. Conifer roots contributed to live root biomass only in the uncut forest. After logging, live conifer roots were not a significant component of the live root biomass. In 3- and 5-year-old cutblocks, the live root component consisted of *Pteridium* roots (rhizomes), but they are only about one-fourth as strong as conifer roots and so contributed little strength to the soil. *Ceanothus* began to occupy the areas 7 years after logging and had completely revegetated the cutblocks 12 years after logging. The relative strength of brush roots < 17 mm in diameter weighted by the biomass in each size class, was 1.60 times the strength of the conifer roots. Consequently, the relative reinforcement by live roots in the brushfields was about 60 per cent of that in the uncut conifer forest. The brushfields apparently began to senesce, and the relative effect of live roots in the 20- to 25-year-old cutblocks was about 40 per cent of that in the uncut forest.

The reinforcement by live roots and that by dead roots is the total reinforcement action which the roots provide to the soil. Within the cutblocks studied, this reinforcement action drops to its low point about 7 years after logging, when it was about 35 per cent of that of the uncut forest. When brush invaded the cutblocks, root reinforcement recovered to about 70 per cent of that in the uncut forest, but again decreased as the brushfield aged and decay of the residual conifer roots progressed.

Given sufficient time without disturbance, the brushfield will eventually yield to a coniferous forest. If this transition is gradual, reinforcement by roots will slowly return to that of the uncut forest as projected (Fig. 3). If the brush is killed in an attempt to establish conifers more quickly, however, the strength of the soil-root matrix would be expected to again drop rapidly as the dead brush roots decay and before the small conifer roots replace the brush roots.

Factor of safety analysis has been applied by O'Loughlin (1972), Wu et. al (1979), and others to slopes with and without roots. The factor of safety provides an index of the relative stability of slopes. If, for a particular storm return period or soil water condition, the factor of safety is less than 1, the slope is considered unstable. Using this concept, if the factor of safety is 1 when relative reinforcement was 0.3 (Fig. 3), slides caused by loss of root strength would not be expected in the logged areas because the minimum total reinforcement always exceeded 0.3.

If, however, the factor of safety was 1 when reinforcement was 0.4, areas logged from 4 to 8 years earlier would be vulnerable to increased sliding, but younger or older cutblocks would not. Similar analyses, based on locally obtained information, would give land managers a tool to evaluate the effect of logging and subsequent vegetative recovery on sensitive slopes.

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TABLE 1. Correlation between *in situ* shear strength and the dry weight of live roots, by various size classes, for a mature Pinus contorta stand growing on coastal sands, northern California.

Diameter of live roots (mm)	Squared correlation coefficient	Diameter of live roots (mm)	Squared correlation coefficient
<2	0.68	<2	0.68
2-5	0.67	<5	0.72
5-10	0.51	<10	0.76
10-17	0.56	<17	0.79
17-25	0.18	<25	0.72
>25	0.03	Total	0.55

TABLE 2. Live root shear strength and ranking (superscripts) by root diameter for species from the mixed conifer area, northern California 1/

Species	Root Diameter (mm)					
	2	5	10	17	25	50
	-shear strength (N)-					
Sambucus callicarpa	77^{2}	449^{1}	1600^{1}	4096^{2}	$7\ 974^{3}$	$25\ 436^{5}$
Ceanothus velutinus	61^{4}	336^{4}	1399^{3}	4485^{1}	$10\ 888^{1}$	$58\ 386^{1}$
Castanopsis chrysophylla	76^{3}	393^{2}	1400^{2}	3781^{4}	$7\ 866^{4}$	$30\ 070^{3}$
Arbutus menziesii	39^{9}	280^{5}	1239^{4}	3863^{3}	$8\ 830^{2}$	$39\ 019^{2}$
Pseudotsuga menziesii	57^{5}	266^{6}	946^{6}	2658^{5}	$5\ 819^{5}$	$25\ 538^{4}$
Libocedrus decurrens	95^{1}	349^{3}	995^{5}	2113^{8}	$4\ 355^{7}$	$14\ 218^{8}$
Abies concolor	49^{6}	241^{8}	849^{8}	2286^{6}	$4\ 767^{6}$	$18\ 455^{6}$
Pinus lambertiana	43^{8}	253^{7}	879^{7}	2167^{7}	$4\ 063^{8}$	$11\ 844^{9}$
Pinus ponderosa	44^{7}	200^{9}	689^{9}	1871^{9}	$3\ 972^{9}$	$16\ 281^{7}$

1/ Species listed by decreasing rank averages over all diameter classes.

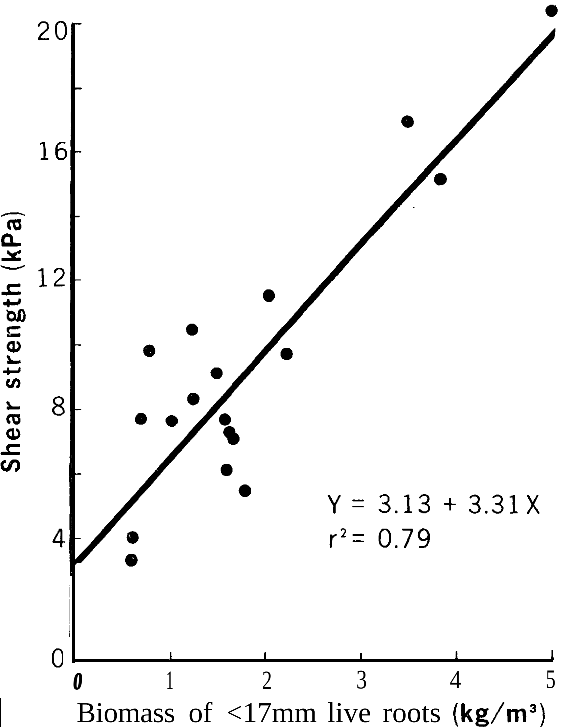

FIGURE 1. *In situ shear strength of the root-soil matrix increased as the dry weight of live roots < 17 mm in diameter increased, in a mature* Pinus contorta *stand growing on coastal sands.*

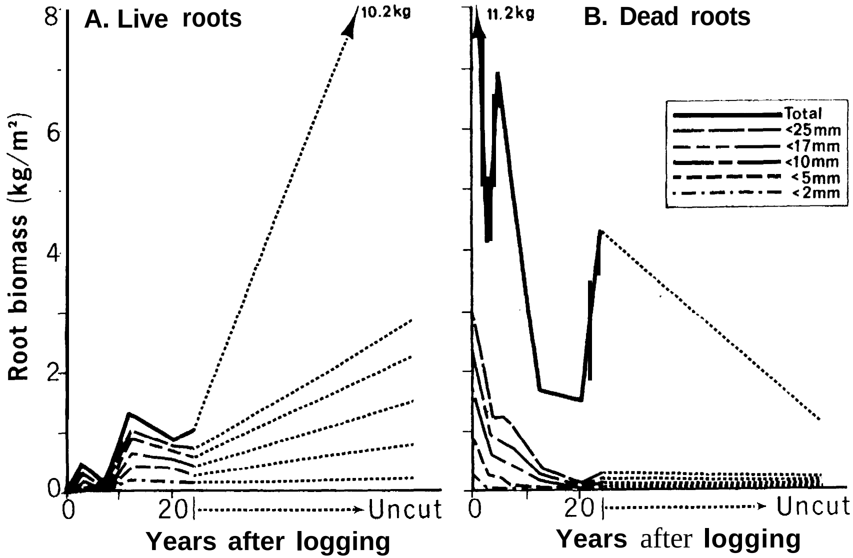

FIGURE 2. *Live root biomass increased and dead root biomass decreased with increasing time after clear-felling in the mixed conifer forest study area.*

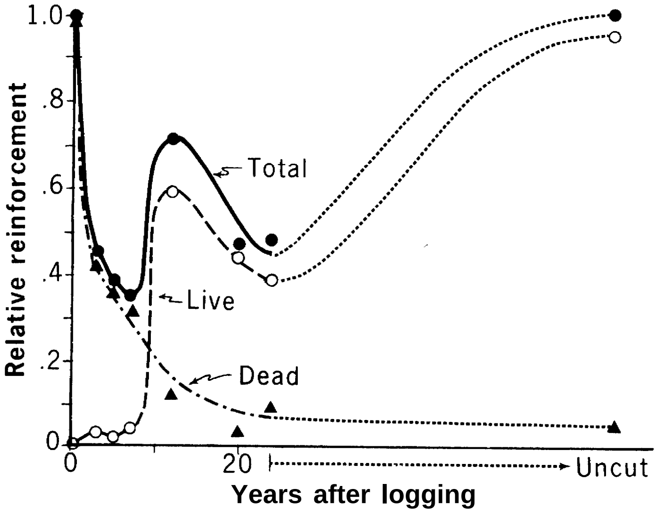

FIGURE 3. The relative reinforcement of soils by live roots generally increased while that by dead roots rapidly decreased with increasing time after clear-felling. The total reinforcement by live and dead roots dropped to a low point about 7 years after logging.