Comments from Jesse Noel via email:

September 19, 2016

Jim, please include this as addendum to my WDR comments: http://kottke.org/16/09/the-internet-of-trees-how-trees-talk-to-each-other-underground

September 16, 2016
James Burke:

Have you, or has some Geologist evaluated the effect of loss of root strength and root depth on the soils found in the 303d listed portion of Elk River pursuant to this WDR to determine whether reduction of root strength and depth constitutes a statistically significant factor for discharge or loading? As you may recall, in the 1980's when discharges associated with timber harvest activities were tolerable, Elk River forest cover was largely 70 to 110 years or older in age. It was both feasible and practicable and profitable to manage the timberland at this level. Please apply the redwood root density study by Ziemer and Lewis that I sent you earlier when you make such determination. I would like to see and comment on your calculations.

Second, does it follow from: "the remaining requirements for erosion control from Cleanup and Abatement Orders for HRC's timberlands in the North and South Fork of Elk River will be incorporated in this Order for a more efficient management of related monitoring and reporting." that while the entire watershed is listed under 303d, the main stem Elk **will not be included in the WDR**? If so, how does NCRWQCB intend to prevent controllable sources of discharge from harvest in the main stem portion from violating the basin plan or other laws? Is this an oversight, or does the WDR purposefully intend to harm the fishery and the residents?

Thank you for your assistance with these issues,
Jesse Noell

James Burke,

A correction, actually the study is one of root biomass instead of root density.

The group selection units are essentially small clear cuts; similar to the Ziemer study. Please disclose if and how you modeled the effects of converting 100 year old redwood forest (600 to 1,000 sq. ft. basal area commonly found in 1980's THPs in Elk River) root biomass where the selection silvicultural method calls for reduction to 75 sq ft of basal area. Is this a linear relationship? Or is it driven by a series of reinforcing positive feedbacks? As there will be fewer large roots and no deep roots at some point in time after conversion, how does this loss of strength combine with the increased effective rainfall post harvest? Does the increased saturation and pore pressure and the fewer large roots and little or no deep rooting increase propensity for debris sliding? Soil creep? Pipe collapse? What happens when pipes collapse: does the blockage cause saturation upslope to skyrocket and increase propensity for torrenting? Do large roots that rot, or burn out, form the underground drainage flow paths known as pipes? Does high levels of root strength serve to keep pipes from collapsing? Is soil pipe collapse why Railroad Gulch has been experiencing such severe torrenting and sedimentation of late?

Doesn't HRC model soil creep rates based on the assumption that the rate cannot be altered by anthropogenic impacts, and that soil creep accounts for the bulk of discharge to Elk River?

Please shed some light on all of this before response to public comment.

Thanks,
Jesse Noell

September 5, 2016

1). “While the mitigations described in the original analysis generally remain the same, and the new measures will be equivalent in mitigating or avoiding a potentially significant effect on the environment and themselves will not result in a potentially significant effect on the environment,”-----a) where does the original analysis differ? b) how are the new measures equivalent and by what metric? c) are the mitigations required to be effective? d) to what extent is the effectiveness of the mitigations enforceable? e) to what extent do the mitigations (after enforcement) assure that environmental injustice and environmental inequity will be fully avoided? Will the WDR avoid maintaining nuisance conditions, or will the WDR perpetuate nuisance conditions over an extended future?

2). “Water quality impacts from logging and associated activities primarily lead to: 1) an increase in sediment production and loading; and 2) elevated water temperatures.”

At the Elk River sub-basin or tributary scale what is the range and mean increase in sediment production from logging and associated activities over the time period 2002 to present?

What relationship between recent tributary harvest and sediment production / loading is evidenced by 1) the ROWD and 2) the WDR analysis and 3) restoring older forest cover?

Peak flow increase from logging and associated activities primarily was found to lead to increased nuisance flooding conditions that primarily threaten the lives and damage the property of residents; does the state policy (WDR) that permits peak flow increase from logging and associated activities (>5% in the South Fork, >5% on the

North Fork) purposefully cause systematic, deliberate, or ongoing environmental inequity and environmental injustice? See WQ analysis of peak flow and cumulative aggradable sediment, circa 2002.

3. “These impacts result from a complex interaction between inherent watershed characteristics, such as geology and geomorphology, external natural processes, such as climate and timing of stochastic events (i.e. large storms, earthquakes, fires), type of management practices, and the extent and rate of watershed area disturbed. Increased sediment production is the result of greater incidence of landsliding, surface and gully erosion, and increases in channel erosion due to higher runoff rates.” How will the decreased root concentrations in the soil that will result under the proposed WDR interact to create impacts to water quality that could be avoided under the community forest alternative? See attached study by Ziemer re: redwood roots, figure 3, 4, 5, etc. Looks like the WDR is going to reduce roots in the soil at depths of .66 meter to 1.33 meter by about 20%. To what extent does a 20% reduction roots at that depth reduce cohesion, increase land sliding and soil creep rates, and pipe erosion? See Figure 3 of attached.

4. “Increased sediment production is the result of greater incidence of landsliding, surface and gully erosion, and increases in channel erosion due to higher runoff rates.” How much will the incidence of land sliding, surface and gully erosion, and channel erosion be increased under the WDR as a result of lessened root mass as compared with forest management that maintains forest older than 65 years? See attached study by Ziemer re: redwood roots, figure 4, etc.

5. “Over time, sediment transported from the upper tributaries has been deposited in low gradient downstream reaches and has resulted in ongoing aggradation, encroachment of riparian vegetation onto relatively recent fine sediment deposits, and an increased incidence of overbank flooding which has impacted the downstream residential community.”

What percent of the “sediment transported from the upper tributaries has been deposited in low gradient downstream reaches and has resulted in ongoing aggradation” results from the State policy that sediment discharge is only required to be controlled “to the extent practicable”, or “to the extent feasible”? Does this policy purposefully implement systematic, deliberate, or ongoing environmental inequity and environmental injustice that could be avoided by the Community Forest alternative? Is application of this policy proper in Elk River under CEQA, NEPA, CWA , our Constitutions, and the APA ?

6. “The draft Order includes requirements to: prevent new sediment discharge, including forest management (including harvest rate); riparian protection; roads management; landslide prevention; and wet weather requirements.” Does the Order prevent all new sediment discharge, or just to the extent feasible or practicable?

7. “The Technical Report provides the technical basis for the Action Plan for Upper Elk River Total Maximum Daily Load (TMDL), which the Regional Water Board adopted on May 12, 2016. The draft Order is a primary implementation component of the TMDL, but other implementation actions are also underway.” Are these other implementation actions funded by the state budget –where is the money? How much money is necessary?

8. “These implementation efforts are outside the scope of the draft Order.” Is it proper for a WDR MNDeclaration to rely on unfunded, unallocated, hypothetical, unidentified, unimplemented, unpermitted (CESA, ESA), speculative--- “other implementation actions” that are way “outside of the draft Order” as meaningful and enforceable mitigations?

9. “Restoration and remediation efforts in the Upper Elk River as well as the downstream impacted reach, combined with the additional layer of environmental protection provided by the Order are expected to ensure that existing cumulative water quality impacts are abated over time, and beneficial uses are ultimately restored and protected.”This statement is a travesty (false flag) because it is obvious that by converting the channel from the natural

deeply incised channel with riparian forest to a wide V shaped channel by so called "***restoration and remediation"*** will obliterate the shade cover and root strength mechanism that provide habitat that was so good for coho. The Residents' alternative that is reasonably designed to restore and remediate (in a feasible and practicable period of time and money) is to create a community forest that is logged from below to restore old growth levels of forest that maximize the biological potential---not just for fish and wildlife, but to maximize the sequestration of carbon, prevent methane release by avoiding compaction and bring back the river and fishery---while providing public access. The jobs that were sacrificed when timber destroyed the highly productive forest cover would return, and tourism and fishing would increase. Ironically, this alternative is the only project that can restore and remediate.

See figure 4 for live redwood roots kilograms/meter sq. post logging.

ROOT BIOMASS IN REDWOOD AND MIXED CONIFER FORESTS
(Robert R. Ziemer And Jack Lewis, PSW Redwood Sciences Lab)

SUMMARY

The death and decomposition of tree roots following logging might reasonably be expected to result in a loss of soil cohesion due to weakened root reinforcement. Ziemer (1981a) has shown how under certain circumstances this can lead to slope failure. To test his hypotheses, Ziemer investigated the strength of live and dead roots of various species in the laboratory (Ziemer, 1981b). Soil samples were collected from redwood and mixed conifer forest stands at various stages of succession following logging and the roots separated and weighed. A cluster sampling method was used within each forest stand. Previous publications reported only on the mixed conifer data. This paper summarizes Ziemer's root biomass data for both mixed conifer and redwood stands and investigates optimum cluster size and required samples sizes for future sampling designs.

METHODS

Studies of tree roots have been plagued by an inability to produce statistically significant results. The tremendous variances are seldom reported. Reynolds (1970) reported standard errors from ten random 425 cc augur samples ranging from 11 to 95 percent of the mean for less-than-6 mm root biomass. His average was about 30 percent and he estimated that 100 samples might be required to show significant differences between depths or concentric zones around a tree. Compared with our findings, that appears to be an optimistic estimate. Ziemer (1981) estimated that if 3200 cc samples were used, sample numbers on the order of 10^5 would be required to determine a trend in biomass related to time after logging.

It was on that basis that a sampling unit of one square meter by 1-1/3 m depth was chosen the root biomass study. The large sampling unit was designed to reduce the number of required samples to a manageable level. Using such a large sampling unit however made simple random sampling difficult, and a cluster sampling design was chosen instead.

Random samples of 2-4 clusters were selected from 6 redwood and 7 mixed conifer stands selected to represent successional stages following logging. Within each forest type, stands of similar soils, surrounding vegetation, climate, and management history were selected. The redwood stands included old growth and ages 5, 11, 24, 43, and 65 years. The mixed conifer stands included old growth and ages 3, 5, 7, 12, 20, and 24 years.

Each cluster consisted of several one-meter sampling units contiguous to an unsampled two-square-meter access pit. Sampling units blocked by tree trunks or boulders were not sampled. This resulted in varying cluster shapes and sizes. The number of sampling units measured in each cluster varied from 4 to 11. Most of the redwood clusters had 6 sampling units. The soil from each sampling unit was screened, and roots were extracted, separated into live and dead components, washed, sorted into 6 size classes, dried at 70° C., and weighed.

ESTIMATING BIOMASS AND ITS VARIANCE

When analyzing a cluster sample with unequal-size clusters, the best approach is often to assume a linear relationship of cluster total (y_i) to cluster size (m_i) and employ a weighted regression approach, wherein weights are inversely proportional to the variance about the regression line. One of three variance models is usually employed: (1) $\sigma_i^2 \propto m_i$, (2) $\sigma_i^2 \propto m_i^2$, or (3) σ_i^2 constant. These variance models result in different estimators. If the number of sampled clusters is *n*, then the best linear unbiased estimators (BLUE) for the cluster mean per sampling unit under the three models are, respectively:

$$\bar{y}_{CL,rm} = \sum y_i \Big/ \sum m_i \quad \text{(ratio of means)} \tag{1}$$

$$\bar{y}_{CL,mr} = \frac{1}{n} \sum y_i / m_i \quad \text{(mean of ratios)} \tag{2}$$

$$\bar{y}_{CL,reg} = \sum y_i m_i \Big/ \sum m_i^2 \quad \text{(regression)} \tag{3}$$

The three estimators are equivalent when m_i is constant. The ratio of means estimator is equivalent to the grand mean. Because clusters with more sampling units influence this estimator more than smaller clusters, the ratio of means estimator is biased, but it is often the most precise of the three. The mean of ratios estimator is equivalent to the mean of cluster means and is unbiased. The regression estimator is not considered here because, for root biomass, the constant variance assumption is unrealistic. The variance of cluster biomass is expected to increase with cluster size, and, if sampling units are independent, variance should be proportional to cluster size. Because there was significant variance among clusters and cluster sizes varied from 4 to 11, the risk of bias in the ratio of means estimator seemed considerable. Therefore we elected to employ the mean of ratios estimator, i.e. the mean of cluster means, for estimating root biomass.

An estimator for the variance of any of the $\bar{y}_{CL}$ estimators is:

$$\hat{V}\left[\bar{y}_{CL}\right] = \frac{N-n}{N} \frac{s_{BLUE}^2}{n\bar{M}^2} \tag{4}$$

where *N* is the number of clusters in the population, $\bar{M}$ is the mean cluster size in the population, and

$$s_{BLUE}^2 = s_y^2 - 2\bar{y}_{CL} s_{my} + \bar{y}_{CL}^2 s_m^2 \tag{5}$$

in which s_m^2, s_y^2, and s_{my} are the sample variances and covariance between m_i and y_i. In our stands we did not know *N* or $\bar{M}$. These are not an inherent property of the stands, since cluster sizes were based on practicalities, but the mean sampled cluster size ($\bar{m}$) can be substituted as an approximation for $\bar{M}$. Also, we know that *n* is small relative to *N* so the finite population correction factor, $(N-n)/N$, can be ignored. We therefore used the approximate variance expression:

$$\tilde{V}\left[\bar{y}_{CL}\right] = \frac{s_{BLUE}^2}{n\bar{m}^2} \tag{6}$$

The standard error of the estimated cluster mean per sampling unit is then $s_{BLUE} / \left(\bar{m}n^{0.5}\right)$.

RESULTS AND DISCUSSION

In the following sections, all biomass values refer to live root biomass unless explicitly stated otherwise. Dead roots comprised a very small portion of the total biomass in old growth stands (particularly in redwood) for all sizes and depths (Figs. 1 and 2).

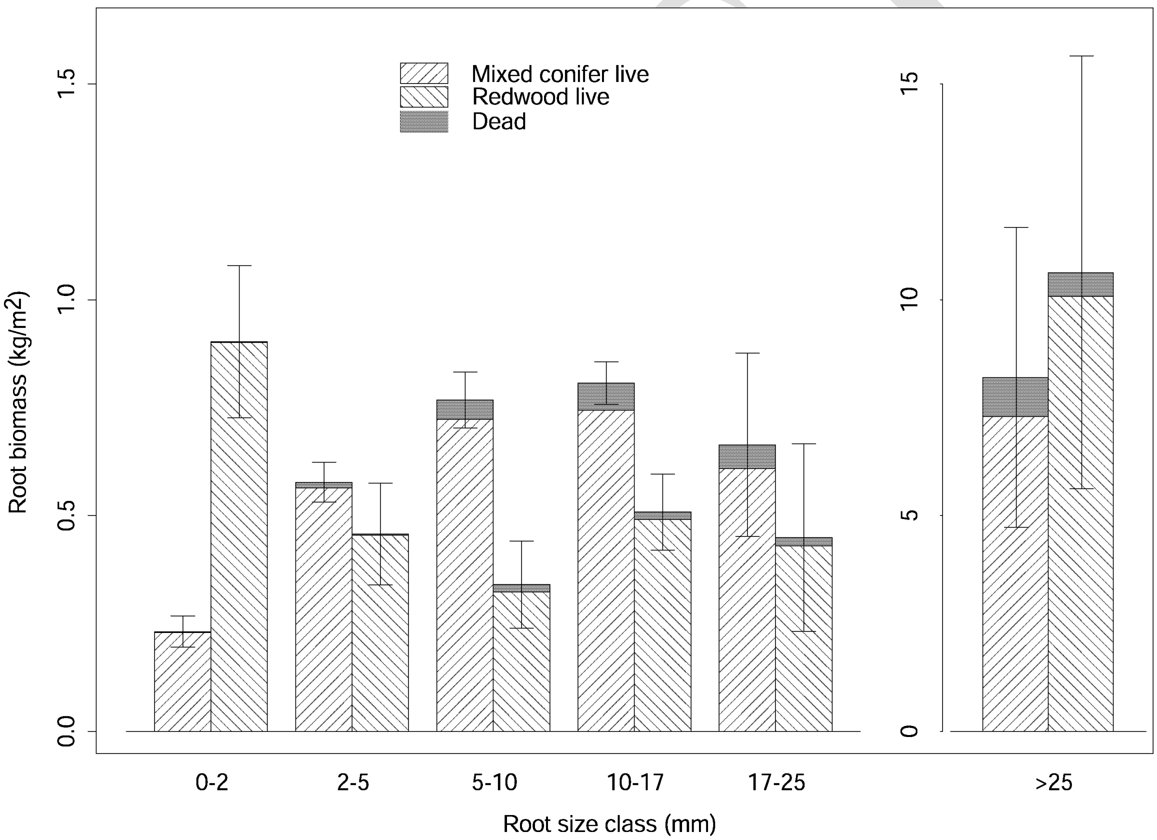

Figure 1. Live and dead root biomass by size class, all depths combined. Error bars designate one standard deviation.

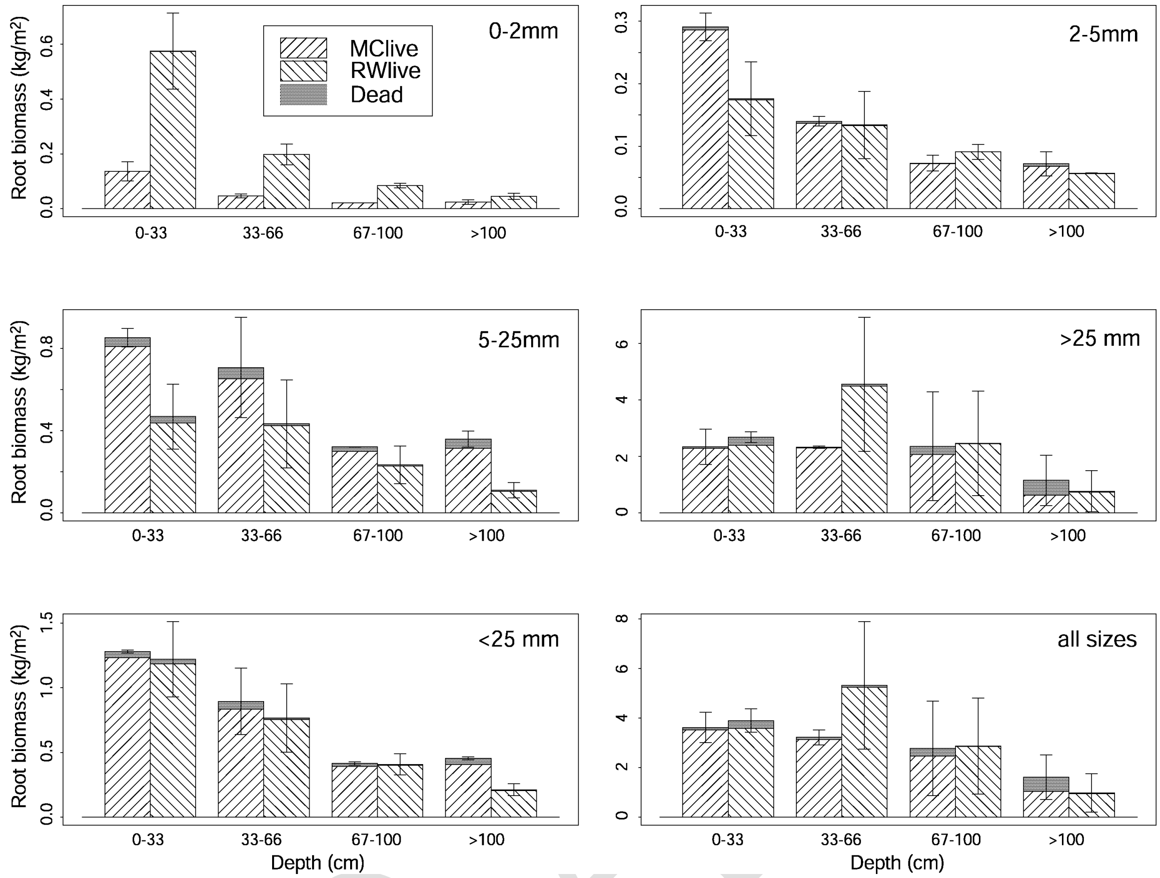

Figure 2. Live and dead root biomass by depth and size class. Error bars designate one standard deviation.

Total and Fine Root Biomass in Old Growth Stands.

Total live root biomass was 10.2 kg/m^2 in the uncut mixed conifer stand and 12.7 kg/m^2 in the virgin redwood. By comparison, in old-growth coniferous forests dominated by Douglas-fir (Grier and Logan, 1977; Santantonio et al., 1977) total root biomass ranged from 10.5 to 20.9 kg/m^2. Outside of these studies, the largest reported value for root biomass in coniferous forests has been 8.5 kg/m^2 in a 200-year-old stand of spruce (Picea abies) in the USSR (Santantonio et.al., 1977). On the other hand, in some tropical and subtropical forests, higher values up to 32.8 kg/m^2 have been reported.

Biomass of fine (less-than-5mm) roots was 0.79 kg/m^2 in the uncut mixed conifer stand and 1.35 kg/m^2 in the virgin redwood. This latter value exceeds nearly every value for fine roots yet reported in the literature, including tropical and subtropical forests. Fine root biomass in old growth forests dominated by Douglas-fir varied from 0.79 to 1.30 kg/m^2 (Grier and Logan, 1977). Studies from a wide variety of forests indicate surprising uniformity in fine root biomass, with values generally varying from 0.5 to 1.0 kg/m^2 in stands over 10 years old. Santantonio et al. (1977) indicates that fine root biomass often appears to reach a peak early in stand development, subsequently levelling off. However, neither of our forest types had reached their peak levels by the age of 24 years (Fig. 3a,c).

It appears that coniferous forests of the Pacific Northwest, particularly redwood forests, are somewhat above average in fine root biomass. This could reflect extensive and persistent development of absorbing roots to exploit the plentiful soil moisture which is available throughout most of the year.

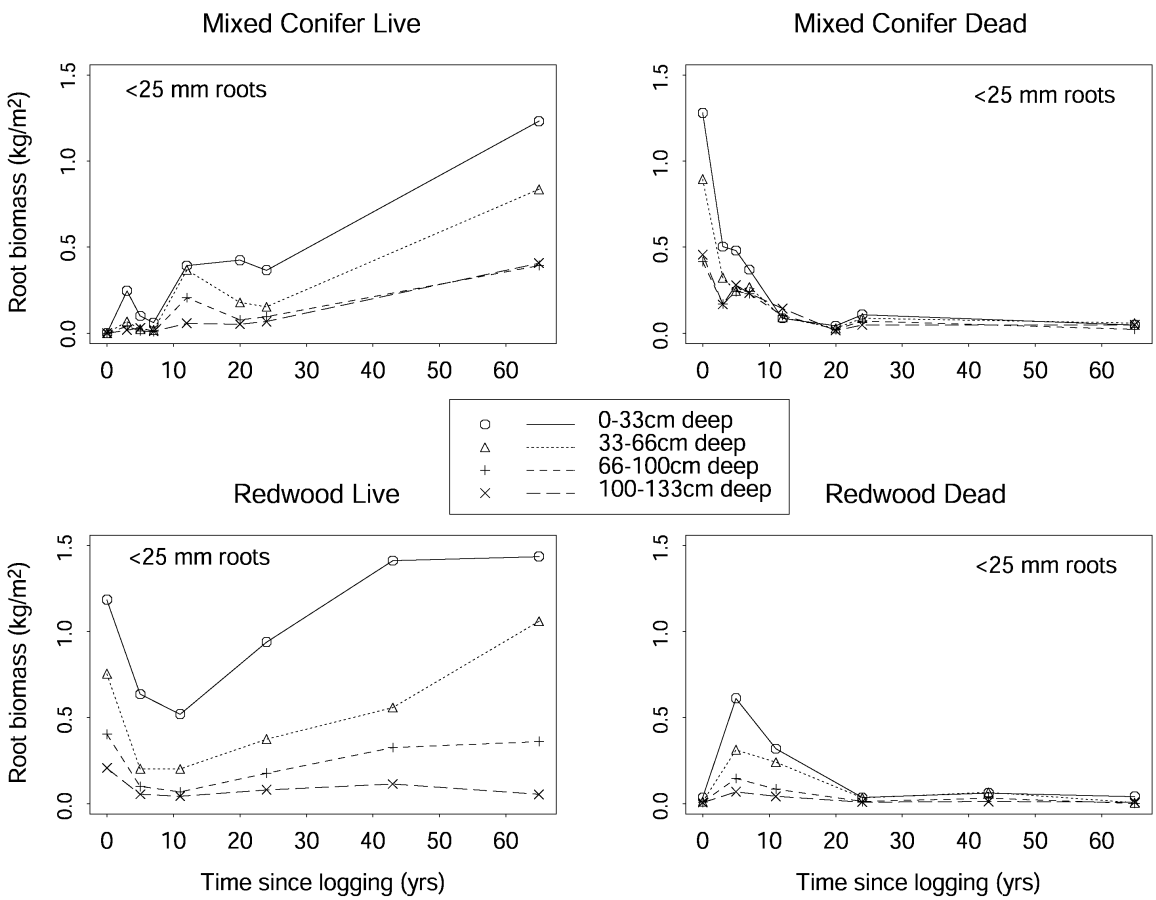

Figure 3. Live and dead fine root biomass (< 25 mm) by stand age.

Root Size Distribution in Old Growth Stands.

There is a marked difference in the size distribution of roots between the old growth redwood and mixed conifer stands (Fig. 1) Although total (live and dead) less-than-25 mm root biomass was very similar, biomass of less-than-2 mm roots was over 4 times as great in redwood. In less-than-2 mm roots redwood had an average 0.90 kg/m^2 contrasted with 0.23 kg/m^2 for mixed conifer forest. On the other hand, in 2-to-25 mm roots, redwood had only 1.75 kg/m^2 as opposed to 2.82 kg/m^2 in mixed conifer forest. Roots bigger than 25 mm in diameter were by far the largest component in terms of biomass, being about 10.6 kg/m^2 in redwood and 8.2 kg/m^2 in mixed conifer forest.

Depth Distribution of Roots in Old Growth Stands.

According to most studies to date, the majority of forest tree roots lie in the upper 50 cm of soil and most of the absorbing roots are in the upper 20 cm. This study is in general accordance with those, although our depths of measurement were in one-third meter increments. The distribution of roots does, however, depend on root size (Fig. 2). Less-than-2 mm roots are concentrated most heavily near the surface. Greater-than-25 mm roots are distributed evenly throughout the upper meter in mixed conifer and, in redwood, concentrated most heavily in the middle of the top meter, tapering off below a meter in both types. Intermediate size classes have intermediate depth distributions. Biomass is skewed towards the surface, but not as extremely as in the case of very fine roots. Considering all size classes, the depth distributions of redwood and mixed conifer forest are quite similar, with one possible difference. Mixed conifer had proportionally greater biomass below a meter in depth in nearly every size class. The individual differences are not all statistically significant, but biomass of all roots less than 25 mm in diameter was about twice as great in mixed conifer.

<u>Changes in Live and Dead Root Biomass After Logging.</u>

Root biomass in several different ages of cutblocks and second growth stands were charted along with the old growth forests (Figs. 3 and 4). Since the cutblocks were similar in soil type, depth, slope, aspect, elevation, original forest density, and silvicultural history, these graphs may be considered as representations of chronological development in the two forest types.

In mixed-conifer, the old growth is placed at 65 years after logging, on the assumption that most of the net change to old growth root biomass levels will have occurred by then. All roots are assumed dead immediately after logging. Thus live root biomass at age zero is plotted as zero and dead root biomass is plotted as the sum of live and dead roots from the old growth stand. The changes in live and dead roots reflect a successional sequence of extensive colonization with bracken fern (<u>Pteridium</u> <u>aquilinum</u>) by age 3, followed with brushfields by age 12. The overall trend of increasing live root biomass with time since logging was interrupted after each of these stages reached its peak. It seems unlikely that in any given cutblock an actual decrease would occur as a result of plant competition at such times. The declines shown in Figure 3 therefore probably reflect differences in succession between the cutblocks studied. Of course, if vegetation were killed in an attempt to establish conifers more quickly, a decline would be expected, but these cutblocks were not treated as such. The dead mixed conifer biomass curve reflects the decaying of roots that were killed by logging, with insignificant bumps corresponding to the decline of the fern and brushfields.

In redwood, the 65-year value is actually from a 65-year-old stand. Since redwood is a sprouting species, roots do not die immediately upon cutting. Thus the old growth live and dead root biomass are plotted at age zero. The live root biomass does, however, decline after logging as the roots come into equilibrium with the drastically reduced above ground biomass. Live less-than-25 mm biomass reached a minimum 11 years after logging. Thereafter it gradually increased to pre-logging levels by age 65, except in the layer below a meter in depth. As with the mixed conifer areas, in this layer live root biomass less than 25 mm remained near or below 0.1 kg/m^2 in all but the virgin stands (Fig. 3).

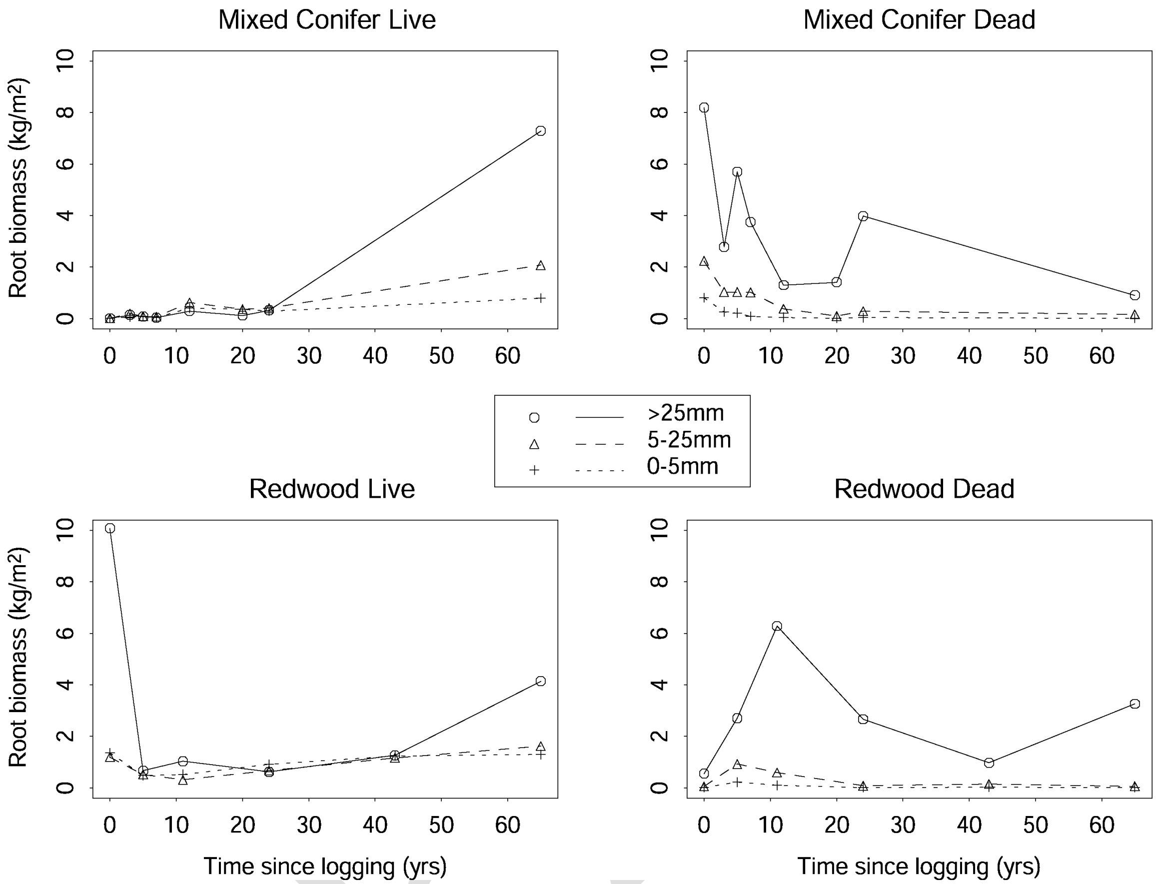

Figure 4. Live and dead fine root biomass (< 25 mm) by stand age.

Dead less-than-25 mm biomass in redwood areas peaked 5 years after logging, even though live root biomass did not appear to reach its minimum until age 11, particularly in the top soil layer. Apparently, decomposition of the large biomass component which had died in the first five years exceeded new senescence between years 5 and 11.

Live-plus-dead root biomass suffers a decline after clearfelling, and full recovery appears to take well over 25 years in the less-than-25 mm fraction (Fig. 5). Larger roots are even slower in returning to prelogging levels. In the mixed conifers the decline in roots appears to be more rapid and of greater magnitude than in the redwood forest. Biomass dropped from about 3.0 kg/m^2 to 1.5 kg/m^2 in only 3 years, and to 0.84 kg/m^2 after 20 years. In redwood, by contrast, biomass dropped from 2.7 kg/m^2 to 1.5 kg/m^2 in 11 years and thereafter began to increase again. Because some redwood roots survive logging, this is not a surprising result.

The following sections give methods and recommendations for optimum cluster size and sample numbers required to construct confidence intervals in future studies, based on the variance estimates from our clusters.

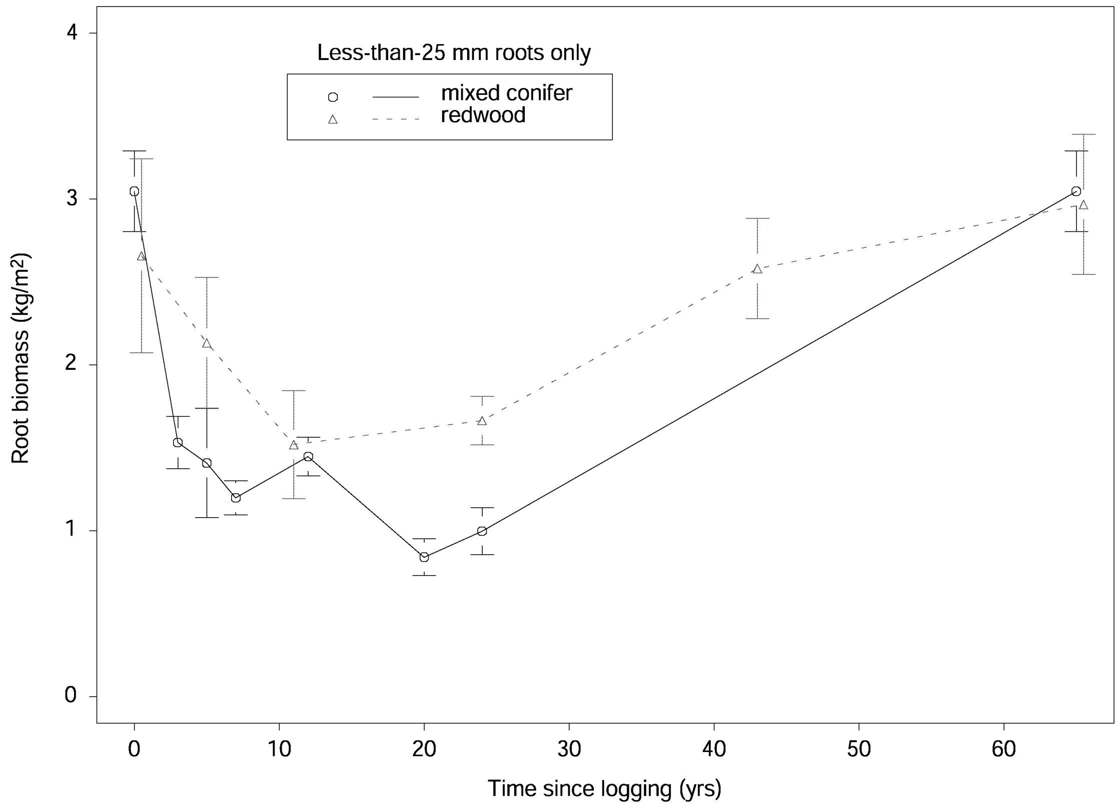

Figure 5. Combined live and dead fine root biomass (< 25 mm) by stand age.

OPTIMUM CLUSTER SIZE

Cluster sampling is a relatively efficient technique commonly used where simple random sampling is impractical. Its major advantage is a decrease in the sampling cost per population element as more and more elements are sampled at one location. In the case of root biomass, it is helpful to dig an access pit at each sampling location to facilitate careful extraction of the sample prior to actual sampling. There may be other per-cluster costs as well, such as the time to move personnel and equipment between clusters. If the cost per cluster is denoted c_l, and the cost per sample is c_2, then a simple expression for the total cost C might be

$$C=c_1n+c_2nm \tag{7}$$

where n is the number of clusters sampled and m is the number of samples per cluster. The dimensions of our access pits were $1\text{m} \times 2\text{m}$. If the cost is expressed in units of soil volume extracted, then, for a 2 m^2 access pit, we have c_1=2 and c_2=1, or

$$C = n(2+m) \tag{8}$$

For a given size of sample (i.e. *nm* constant), many small clusters will give more precise results than a few large ones when clusters tend to be homogeneous relative to the population. In this study, a few large clusters were sampled in each stand or cutblock, thereby economizing but sacrificing precision. In choosing a sampling design, reduced cost should be balanced against reduced precision. This may be done by selecting a cluster size that gives minimum variance (of the estimate) for a given cost or minimum cost for a given variance. For a cost function such as (7) that is linear in *n*, the two problems have identical solutions.

A cluster sample is a special case of a two-stage sample, wherein at the second stage, all sampling units within the first-stage sample are measured. If the number of sampled clusters (first-stage units) is small relative to the number of clusters in the population, the optimum cluster size for a two-stage design with costs given by (7) is

$$m_{opt} = \left(\frac{\sigma_w^2}{\sigma_b^2} \frac{c_1}{c_2} \right)^{1/2} \qquad (9)$$

(Scheaffer et al. 1986). where σ_w^2 is the variance among sampling units within clusters and σ_b^2 is the variance among the true cluster means. These two variance components can be estimated from our cluster samples from each stand using analysis of variance. An unbiased estimator for σ_w^2 is $\hat{\sigma}_w^2 = s_w^2$, the mean square within clusters. An unbiased estimator for σ_b^2 is

$$\hat{\sigma}_b^2 = \left(s_b^2 - s_w^2 \right) \big/ m_0 \qquad (10)$$

where s_b^2 is the mean square between clusters and m_0 is the "average" cluster size (Guenther, 1964):

$$m_0 = \frac{1}{n-1} \left(\sum m_i - \frac{\sum m_i^2}{\sum m_i} \right). \qquad (11)$$

Optimum cluster size was calculated for the cost function (8) from analyses of variance on 78 forest type-age-size-live/dead groupings. In 16 of the mixed conifer groups, and 3 of the redwood groups, the mean square within clusters was greater than the mean square between clusters, thus giving a negative component of variance among clusters. Optimum cluster size cannot be calculated in such cases. The probable reason for these negative values of $\hat{\sigma}_b^2$ is low precision in the mean squares due to our small number of clusters in each stand. Mixed conifer groups had an average of just 2.3 clusters per stand, while redwood had an average of 3.5 clusters per stand.

When calculable optimum cluster sizes are plotted against mean biomass, $\bar{y}$, (Fig. 6) only the optima for live redwood roots appear to be reasonably well behaved. The others are highly variable, with no clear trends according to either size or age. We therefore

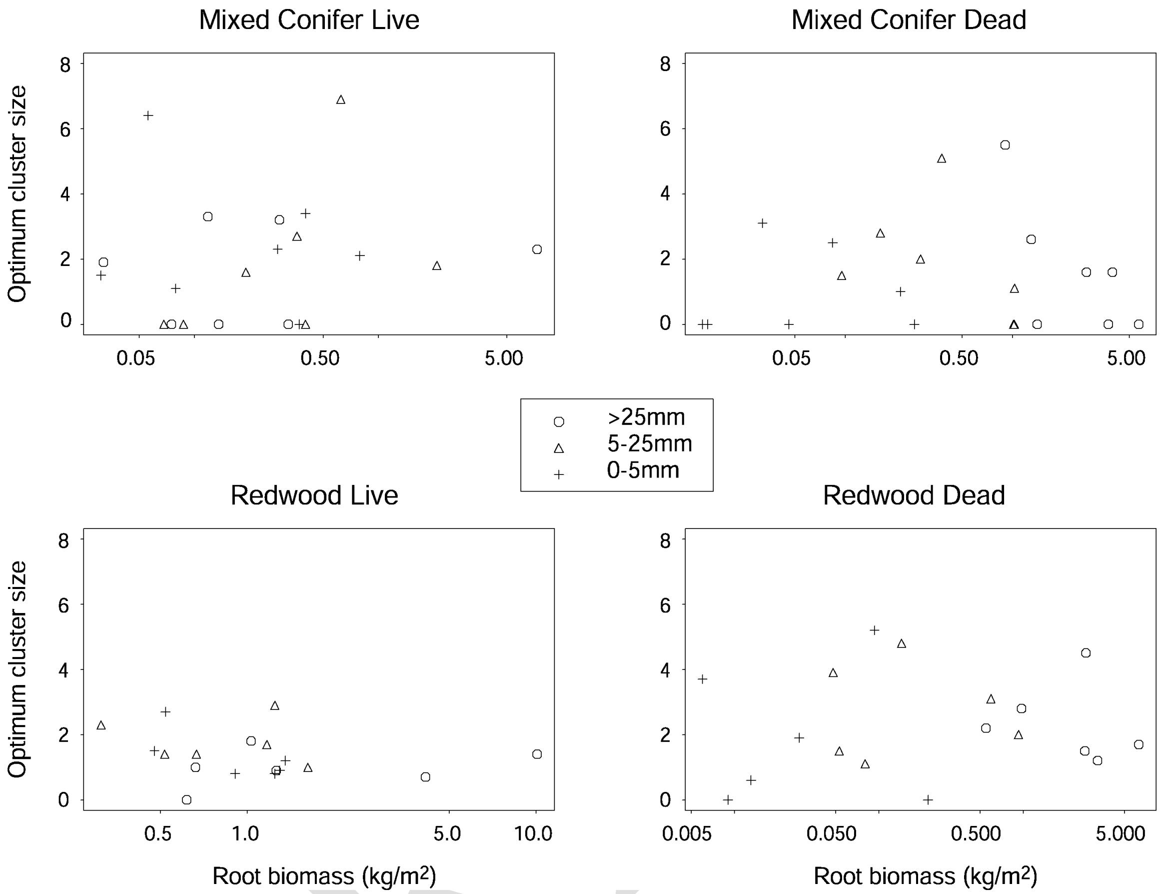

Figure 6. Relation of optimum cluster size to root biomass.

pooled sums of squares across age classes, using nested analysis of variance, to obtain more precise variance estimates. All the variance components were positive, thus giving a single optimum cluster size for each size class of live and dead roots (Table 1). Still, there is no apparent trend in the optima according to these categories, and it is tempting to select a value which might be nearly optimal for any root sizes, live or dead. Fortunately, it is quite possible to do so, because optimum is relatively flat (Cochran, 1977). Thus it is possible to alter cluster size from its optimum while still maintaining a high degree of precision relative to the optimum variance. Relative precision is defined as the ratio of the variance at m_{opt} to the variance at a chosen cluster size m_0. The relative precision of m_0 to m_{opt} is

$$\frac{V\left[\bar{y}_{CL,mr} \mid m_{opt}\right]}{V\left[\bar{y}_{CL,mr} \mid m_0\right]} = \frac{\left(\sigma_b\sqrt{c_1} + \sigma_w\sqrt{c_2}\right)^2}{\sigma_b^2 c_1 + \sigma_w^2 c_2 + m_0 c_2 \sigma_b^2 + c_1\sigma_w^2 / m_0} \tag{12}$$

Table 1. Relative Precision of Alternative Cluster Sizes. Cost coefficients are $c_1=2$ and $c2=1$. Pooled variance components were estimated using nested analysis of variance.

				Relative Precision for Alternative Cluster Sizes			
Species/root class	$\hat{\sigma}_w^2$	$\hat{\sigma}_b^2$	Optimum size	1	2	3	6
RW live 0-5mm	5.11×10^4	8.17×10^4	1.1	99.7	92.6	80.5	55.0
RW live 5-25mm	2.17×10^5	1.43×10^5	1.7	92.7	99.5	93.0	69.9
RW live >25 mm	5.53×10^6	1.20×10^7	1.0	100.0	89.0	75.9	50.8
RW dead 0-5mm	2.85×10^3	2.47×10^3	1.5	95.8	98.2	89.5	64.9
RW dead 5-25mm	4.64×10^4	1.88×10^4	2.2	85.7	99.7	97.8	78.9
RW dead >25mm	1.63×10^7	1.18×10^7	1.7	93.9	99.1	91.8	68.1
MC live 0-5mm	1.25×10^4	3.90×10^3	2.5	81.5	98.7	99.3	83.6
MC live 5-25mm	7.71×10^4	1.84×10^4	2.9	77.0	96.8	100.0	88.1
MC live >25 mm	4.27×10^6	1.20×10^6	2.7	79.6	98.0	99.7	85.5
MC dead 0-5mm	2.03×10^3	1.41×10^3	1.7	93.4	99.3	92.3	68.9
MC dead 5-25mm	4.95×10^4	2.33×10^4	2.1	88.0	100.0	96.6	76.1
MC dead >25mm	9.69×10^6	2.43×10^6	2.8	77.8	97.2	99.9	87.4

For redwood, the relative precision using a cluster size of 1 varies from 85.7 to 100.0%, according to root class. A cluster size of 2 appears to be a slightly better choice for most redwood root classes and is certainly more appealing (unless field procedures are altered to reduce the per-cluster cost) since a cluster size of 1 amounts to abandonment of cluster sampling in favor of simple random sampling with a cost of 3 per sampling unit. The cluster size of 6 used in most of the redwood stands had relative precision from 50.8% to 78.9% and was clearly larger than necessary. For mixed conifer, a cluster size of 2 gives relative precision of at least 96.8% in all classes. A cluster size of 3 does better in 4 of 6 classes, but the precision falls to 92.3% for dead 0-5mm roots.

REQUIRED SAMPLE SIZES

Having chosen an optimum cluster size, it remains to be determined how many clusters of this size are required to achieve a given bound on mean root biomass. We need to predict the variance of $\bar{\bar{y}}$, the mean of cluster means, for a cluster size *m* different from those used in our survey. An unbiased large-population variance estimate, based on a pilot study that used clusters of size m_0, is given by,

$$\hat{V}(\bar{\bar{y}}) = \frac{\hat{\sigma}_b^2}{n} + \frac{\hat{\sigma}_w^2}{nm} = \frac{1}{n}\left(\frac{s_b^2}{m_0} + s_w^2\left(\frac{1}{m} - \frac{1}{m_0}\right)\right) \tag{13}$$

(Cochran, 1963). If we assume approximate normality of $\bar{\bar{y}}$, a 95% confidence interval has half-width of about 2 standard errors. The number of clusters required to achieve a proportional error of *p* is then approximately

$$n = \frac{4}{\left(p\bar{\bar{y}}\right)^2}\left(\hat{\sigma}_b^2 + \frac{\hat{\sigma}_w^2}{m}\right) \tag{14}$$

Because sample size is a function of $\bar{\bar{y}}$, which varies greatly from stand to stand, variance components were not pooled across stands. Table 2 and Figure 7 show required sample sizes estimated for each sampled stand with $p = 0.25$ and $m = 2$. Estimates are highly variable between size classes and stands of different ages. Sample sizes needed are greatest for large roots, but do not differ greatly between redwood and mixed conifer types. Required sample sizes are greater in young stands for live roots and greater in old stands for dead roots For roots less than 25 mm, the average required sample size is 10.1 clusters for live roots in stands at least 20 years of age and 9.6 for dead roots in stands under 10 years of age. For other ages or sizes, required sample sizes are generally much larger. For live and dead roots combined, required sample size is independent of age, averaging 6 and 10, respectively, for mixed conifer and redwood roots less than 25mm.

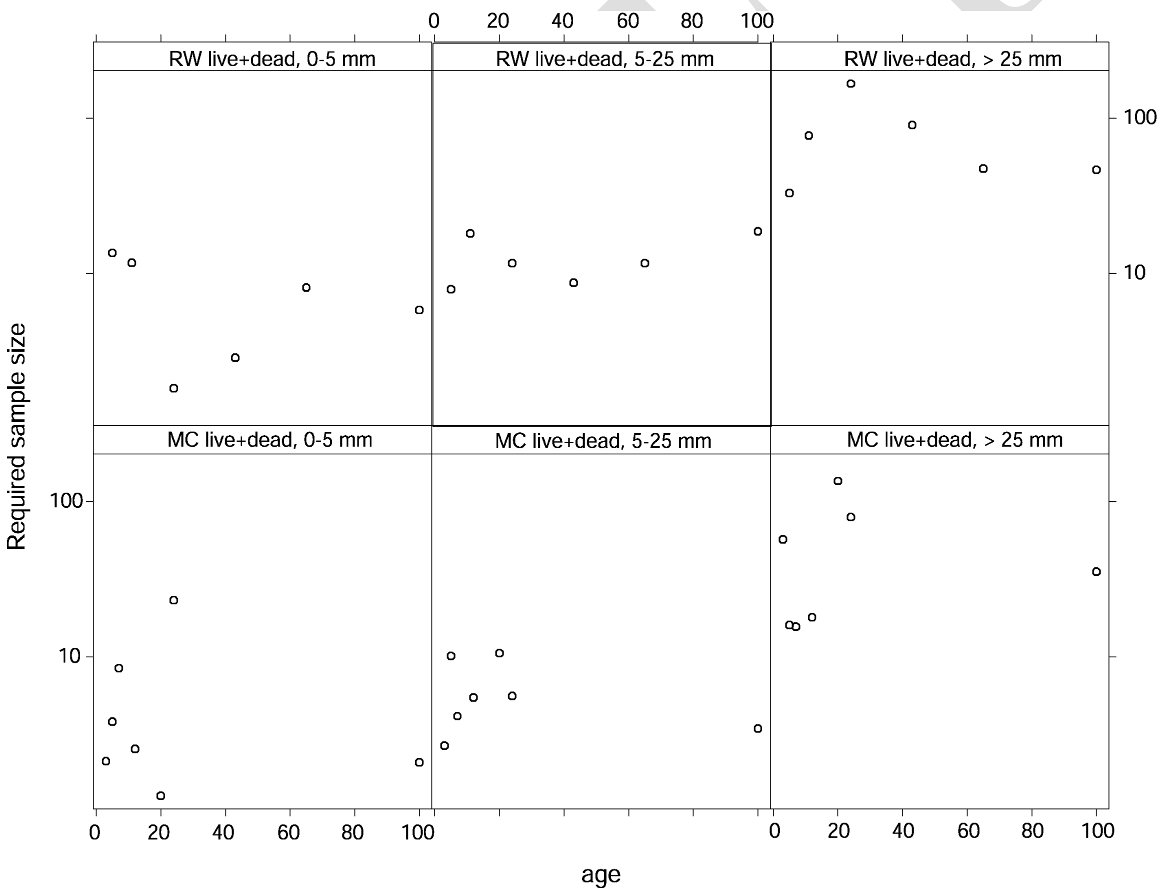

Figure 7. Number of clusters of size 2 required to establish a 95% confidence interval that has half-width no greater than one-fourth of the mean biomass..

Table 2. Number of required clusters for $p = 0.25$ and $m = 2$.

MC				RW			
Age	Root Class	Biomass (kg/m^2)	n	Age	Root Class	Biomass (kg/m^2)	n
OG	Live 0-5mm	792	3	OG	Live 0-5mm	1354	6
	Live 5-25	2076	4		Live 5-25	1244	19
	Live > 25	7290	30		Live > 25	10080	58
	Dead 0-5	15	30		Dead 0-5	6	50
	Dead 5-25	162	21		Dead 5-25	53	34
	Dead > 25	904	230		Dead > 25	549	159
24	Live 0-5mm	283	23	65	Live 0-5mm	1294	9
	Live 5-25	400	17		Live 5-25	1617	13
	Live > 25	323	147		Live > 25	4138	32
	Dead 0-5	32	42		Dead 0-5	9	367
	Dead 5-25	282	17		Dead 5-25	48	136
	Dead > 25	3975	83		Dead > 25	3263	139
20	Live 0-5mm	371	2	43	Live 0-5mm	1243	3
	Live 5-25	360	8		Live 5-25	1166	12
	Live > 25	118	100		Live > 25	1259	183
	Dead 0-5	14	39		Dead 0-5	28	11
	Dead 5-25	95	39		Dead 5-25	143	22
	Dead > 25	1410	159		Dead > 25	967	49
12	Live 0-5mm	401	4	24	Live 0-5mm	906	2
	Live 5-25	624	14		Live 5-25	665	14
	Live > 25	289	58		Live > 25	616	68
	Dead 0-5	46	9		Dead 0-5	13	13
	Dead 5-25	377	4		Dead 5-25	80	35
	Dead > 25	1297	32		Dead > 25	2663	215
7	Live 0-5mm	31	22	11	Live 0-5mm	520	18
	Live 5-25	68	81		Live 5-25	311	64
	Live > 25	32	231		Live > 25	1029	145
	Dead 0-5	84	12		Dead 0-5	93	58
	Dead 5-25	1015	4		Dead 5-25	594	21
	Dead > 25	3743	16		Dead > 25	6281	100
5	Live 0-5mm	79	28	5	Live 0-5mm	476	17
	Live 5-25	87	36		Live 5-25	516	19
	Live > 25	75	415		Live > 25	660	127
	Dead 0-5	214	18		Dead 0-5	218	19
	Dead 5-25	1028	13		Dead 5-25	923	9
	Dead > 25	5703	16		Dead > 25	2702	26
3	Live 0-5mm	56	50				
	Live 5-25	190	82				
	Live > 25	135	439				
	Dead 0-5	259	2				

	Dead 5-25	1026	3				
	Dead > 25	2778	57				

SUMMARY

Cluster sampling can reduce the cost of root biomass studies. In choosing a cluster size, reduced cost must be balanced against loss of precision. For a design using sampling elements one square meter in area and 1-1/3 m deep, it is necessary to dig an access pit the equivalent of about 2 sampling elements in order to facilitate careful extraction of the sample. If the cost of sampling is measured in terms of the volume of the access pit plus the samples, then the optimum number of samples per cluster is close to two for a wide range of root sizes (live or dead) and stand ages in both redwood and mixed conifer forest. For roots greater-than-25 mm in diameter, establishing narrow confidence limits is an enormous task. For smaller roots, it is still a big job--95% limits with a half-width of 1/4 of the mean would typically require sampling 10 clusters, each entailing a 4-m^2 excavation to the maximum rooting depth.

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