A spatial and temporal model of root cohesion in forest soils

M.E. Sakals and Roy C. Sidle

Abstract: Root cohesion is an important parameter governing slope stability in steep forested terrain. Forest harvesting impacts root cohesion, and although the temporal effects have been noted, this dynamic parameter is often assumed to be spatially uniform. A model was developed to simulate the variation in root cohesion on a hillslope resulting from various forest management treatments. The model combines physical data on the horizontal rooting distribution of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) together with a temporal relation of root cohesion decay. Harvesting methods examined include clear-cutting, single-tree selection cutting, and strip-cutting. Model outputs are analysed qualitatively for regions of root cohesion minima and quantitatively for the average root cohesion within the simulated hillslope. A selection cutting simulation maintained the highest average root cohesion value, decreasing to only 81% of the preharvest condition. In contrast, the minimum root cohesion following clear-cutting declined to 38% of the preharvest value. Selection and strip-cutting scenarios resulted in smaller areas of reduced root cohesion that were adjacent to areas with high root cohesion. Such partial cutting methods shorten the period of reduced root cohesion following timber harvesting compared with clear-cutting.

Résumé : La cohésion des racines est un paramètre important de la stabilité des pentes en terrain boisé accidenté. La récolte de matière ligneuse a un impact sur la cohésion des racines et, bien que les effets temporels aient été notés, ce paramètre dynamique est souvent considéré comme spatialement uniforme. Nous avons développé un modèle pour simuler la variation de la cohésion des racines dans une pente, en fonction de divers traitements d'aménagement forestier. Le modèle regroupe des données physiques sur la distribution horizontale des racines du douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) et une fonction temporelle de dégradation de la cohésion des racines. Les méthodes de récolte examinées incluent la coupe à blanc, la coupe de jardinage par pied d'arbre et la coupe par bande. Les extrants du modèle sont analysés qualitativement pour les zones de cohésion minimales des racines et quantitativement pour la cohésion moyenne des racines sur les pentes simulées. La simulation avec la coupe de jardinage permet de conserver la plus forte valeur moyenne de cohésion des racines qui est équivalente à 81 % de la cohésion avant la récolte. À l'inverse, la cohésion minimale des racines après une coupe à blanc diminue jusqu'à une valeur équivalente à 38 % de la cohésion avant la récolte. La coupe de jardinage et la coupe par bande produisent des zones de faible cohésion des racines plus restreintes qui sont adjacentes à des zones de forte cohésion des racines. De telles méthodes de coupe partielle raccourcissent la période pendant laquelle la cohésion des racines est réduite à cause de la récolte de matière ligneuse comparativement à la coupe à blanc.

[Traduit par la Rédaction]

Introduction

Vegetation, particularly trees, plays a critical role in contributing to slope stability through root reinforcement, especially on steep forested slopes prone to shallow rapid failures (Kitamura and Namba 1981; Marden and Rowan 1993; Ekanayake and Phillips 1999). In shallow soils, tree roots may penetrate the entire soil mantle and provide vertical anchors into more stable substrate (Wu et al. 1979; Gray and Megahan 1981; Greenway 1987). Dense lateral root systems in the upper soil horizons form a membrane that stabilizes the soil (Sidle et al. 1985; Tsukamoto 1987). Therefore, the contribution of roots to shear strength of hillslope soils has been included as an additive cohesion component (ΔC) by numerous investigators (e.g., Gray and Megahan 1981; Abe and Ziemer 1991; Sidle 1991).

Timber harvesting significantly increases the potential for shallow mass wasting (particularly debris slides and avalanches) by decreasing root cohesion. Such effects are evidenced by studies worldwide that have documented 2- to 10-fold increases in rates of mass erosion in the period from 3 to 15 years after timber harvesting (Bishop and Stevens 1964; Endo and Tsuruta 1969; O'Loughlin and Pearce 1976). This increase in landslide frequency and volume is related to the period of reduced root cohesion after harvesting and prior to substantial regeneration (Sidle 1991, 1992). Independent tests of the effects of timber harvest on root reinforcement based on mechanical straining of roots have

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confirmed these empirical observations (Burroughs and Thomas 1977; Abe and Ziemer 1991; Commandeur and Pyles 1991).

During the period of decreased root cohesion after timber harvesting, it is necessary to know the spatial and temporal patterns of root cohesion to facilitate best management practices on commercial forest lands (Kitamura and Namba 1981; Watson et al. 1999). Most existing root cohesion models that have been applied to landslide analysis are not spatially distributed (e.g., Wu et al. 1979; Riestenberg and Sovonick-Dunford 1983; Ekanayake and Phillips 1999). Recently, a distributed landslide model that includes the dynamics of root cohesion has been developed and applied at the drainage basin scale with good results (Wu and Sidle 1995; Sidle and Wu 1999; Dhakal and Sidle 2003). This model was initially developed with an average resolution of about 100 m^2 (Wu and Sidle 1995) and more recently applied at a resolution of about 25 m^2 (Dhakal and Sidle 2003); however, no attempt was made to simulate variability in root cohesion within forest stand types (i.e., average values of root cohesion were applied over areas of many hectares). Thus, the objective of the research described in this paper is to develop a model, based on field data, that assesses the spatial (at a scale of 0.25 m^2) and temporal variability of the root cohesion during forest harvesting and stand tending.

Materials and methods

Model development and considerations

The root cohesion model was designed to explore the impacts of various harvesting systems on spatially distributed root cohesion within forest stands of specified structures. The simulated area of forest hillslope is 0.25 ha, an acceptable size to assess variability in root cohesion The resolution of the model is 0.25 m^2; this high resolution should depict the gross morphology of root distributions. Model parameters are as follows:

DENSITY: initial density of trees on the slope (trees per hectare)
AGE: initial age of the trees (years)
HARVEST TYPE: clear-cut, selection cut, and strip-cut
SELECT AGE: the minimum age of trees to be harvested in the select option (years)
SELECT %: percentage of stems to be cut (must be >SELECT AGE) (percent)
CUT STRIP: the width of the cut strip in the strip-cut option (metres)
LEAVE STRIP: the width of the leave strip in the strip-cut option (metres)
HARVEST INTERVAL: period between entries (years)
SPACING: minimum intertree distance for live trees (metres)
YEARS: number of years that the simulation will run (years).

Tree locations are randomly assigned, ensuring that the SPACING variable has been considered. In the selection cutting option, all trees older than SELECT AGE are eligible to be cut. The specified percentage (SELECT %) of the eligible trees are then randomly selected for harvesting. For the strip-cutting option, specified widths (strips) of forest are harvested. During each subsequent harvest, cut strips are located to the left of the previously harvested strip. The planting ratio is held constant: five seedlings planted for each harvested stem based on typical silvicultural procedures and a component for naturally regenerating trees. The thinning age is also constant at 20 years. At this age, the forest is thinned to the preharvest density and the remaining regenerating trees are located in the same locations as the original trees. The final option is the time frame for a particular forest management scenario.

Burroughs and Thomas (1977) calculated the root cohesion from a pure 100- to 200-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) stand in the Pacific Northwest. They reported a range of root cohesion values from 5.0 to 22 kPa; an intermediate value of 12.0 kPa was used to calibrate the model. The calibration simulation assumes a pure 150-year-old stand of Douglas-fir (midpoint of the age range 100–200 years specified by Burroughs and Thomas (1977)) with a density of 300 stems/ha (estimated from photographs). This scenario was modeled and a coefficient was found and applied so that outputs would be in kilopascals. An understory cohesion component of 1.5 kPa, including shrubs and other conifer regeneration, was added based on research by Sidle and Swanston (1982). Following harvesting, the understory component falls to zero and recovers linearly over 5 years. In the selection cutting option, the entire understory is disturbed; in the strip-cutting option, only the understory within the harvested strips is disturbed.

The distributed root cohesion model is theoretical and expands upon previous concepts incorporated in root cohesion research (e.g., Tsukamoto and Minematsu 1987; Sidle 1991; Ekanayake and Phillips 1999) and GIS-based landslide modeling (e.g., Wu and Sidle 1995; Dhakal and Sidle 2003). Assumptions inherent in the distributed root cohesion model include the following:

(1) Root cohesion follows the same spatial distribution as root volume. Previous research found that increased diameter of roots led to increased strength (Burroughs and Thomas 1977) and that increases in root biomass increased soil strength (Ziemer 1981).
(2) A two-dimensional model of root cohesion represents a reasonable biophysical analogy in soils that are shallow relative to the potential root penetration depth of trees. In the case of coastal British Columbia, Washington, Oregon, and coastal Alaska, most soils in steep terrain are <2 m deep (Sidle 1984; Montgomery et al. 1997), and the rooting system of Douglas-fir is capable of deeper rooting (Stone and Kalisz 1991). Previous research has found that tree roots may be present in the entire mantle of shallow soils (Wu et al. 1979; Gray and Megahan 1981; Greenway 1987). It is extremely difficult to quantitatively describe tree root distributions in three dimensions, as witnessed by other researchers (e.g., Eis 1974); thus, any such modeling efforts and interpretations would be very complex.
(3) The rooting system of Douglas-fir can be approximated by a disc of regular radius, regardless of slope. Sources of information regarding this assumption are inconclusive. While some studies claim that roots extend further

in the upslope direction (McMinn 1963), other studies have shown that this is not the case (Eis 1974). Generally, the shape of the rooting system is not circular; however, the model is designed to reflect the population of rooting morphologies.

(4) Root volume distributions, root influence radii, and total root volume values reported in this study are representative of the rooting morphologies of Douglas-fir on failure-prone sites. The data collected on root distributions and extents reasonably agree with other sources (e.g., McMinn 1963; Eis 1987; Kuiper and Coutts 1992).

(5) Root cohesion decay occurs according to the following equation:

$$D = \exp(-kt^n)$$

where D is the root cohesion (kilopascals) and k and n are empirical constants with values for coastal Douglas-fir of 0.506 and 0.730, respectively (Sidle 1991).

(6) Root cohesion contributed by undergrowth is considered spatially uniform, except after forest harvesting activities, based on a value of 1.5 kPa. This value is within the range specified by Sidle and Swanston's (1982) back-calculation (after slope failure) in a mature spruce–hemlock forest in southeast Alaska.

(7) Soils in the modeled hillslope are relatively homogeneous. Root morphology is affected by certain soil conditions (Eis 1987); thus, it is necessary to assume that the modeled slope has relatively uniform conditions related to root anchoring and root growth.

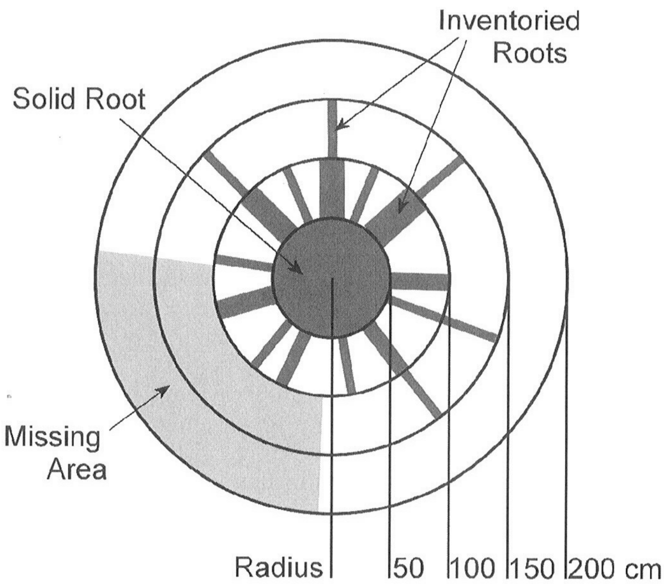
(8) Trees do not vary in productivity in different forest stands or among individuals within a stand. This model excludes dominant–suppressed and competition relationships. The model simulates an average tree, although it is likely biased towards the dominant and codominant trees, as suppressed trees suffer less from windthrow because of low exposure area and protected position within the canopy.

(9) Root cohesion at any point on the hillslope can be expressed by the summation of components from adjacent, individual trees and the undergrowth component.

Field investigations

To quantify tree root distribution, we collected field data for Douglas-fir trees in two experimental forests in the south coastal region of British Columbia: The University of British Columbia Malcolm Knapp Research Forest in Haney, B.C., and the Roberts Creek Experimental Forest on the Sunshine Coast of British Columbia. Mean annual precipitation within the Malcolm Knapp Research Forest ranges from 2140 to 2682 mm (Klinka and Krajina 1986). Long-term mean annual precipitation at Powell River (north of Roberts Creek Experimental Forest on the Sunshine Coast) is 1233 mm. The bedrock underlying both study areas is plutonic hornblende granodiorite and quartz diorite. Site indices for coastal Douglas-fir for all sampling sites ranged from 27 to 32 (predicted tree height in metres at a breast-height age of 50 years). Root systems are strongly influenced by soil type (Eis 1987); thus, root systems were selected in soils that were moderately to well drained, with a silty to sandy texture and 40%–65% coarse fragments. No root systems were

Fig. 1. Conceptual diagram of root inventory showing roots >5 cm in diameter.



sampled in topographically low sites or sites where gleying was present within the 30 cm soil depth below the root plate hollow, as such features may have a high water tables that could influence root morphology. A minimum soil depth of 1.5 m was required in all cases. Only recently exposed root systems were selected because the finer roots of such systems would be preserved. The 20 root systems sampled represented a reasonable cross section of ages.

First, excavation of organic and mineral debris within the root plate was accomplished with hand tools. Second, a measure was made of the vertical and horizontal (radial) extent of the solid root. Third, starting at 50 cm from the centre of the solid root (unless the solid root had a radial extent >50 cm, in which case the first radius would be 100 cm), each root was measured and classified (Fig. 1). This is similar to the horizontal partitioning of Karizumi's (1974) study in Japan. The inventoried root diameter categories are 1–2, 2–5, 5–10, and >10 cm. Roots with diameters >10 cm were measured individually and diameters were recorded. This procedure was repeated with concentric measurement radii increasing by 50 cm until the furthest attached roots with diameters >1 cm were inventoried. Where roots >10 cm in diameter were broken, estimates were made based on the inspection of other root networks of the same size on the same tree. This involved estimating the diameter of the root and of subsequent lateral roots and was only done for roots >10 cm in diameter. The estimated volume of broken roots averaged 2% of the total root volume for all trees. Because the investigated root plates were exposed as a result of windthrow, the position and orientation of the plates were often not acceptable to perform a complete root inventory. The stem and much of the root wad sometimes rested on top of some of the roots and the roots in the direction of the fall often remained in the soil. Thus, the root inventory was conducted on the portion of the root plate that could be reasonably excavated. The eliminated or missing portion was assumed to have similar rooting characteristics as the inventoried portion and thus was interpolated from each concen-

Fig. 2. Inventoried root volume for Tree 1, a 65-year-old Douglas-fir. The legend depicts root diameter.

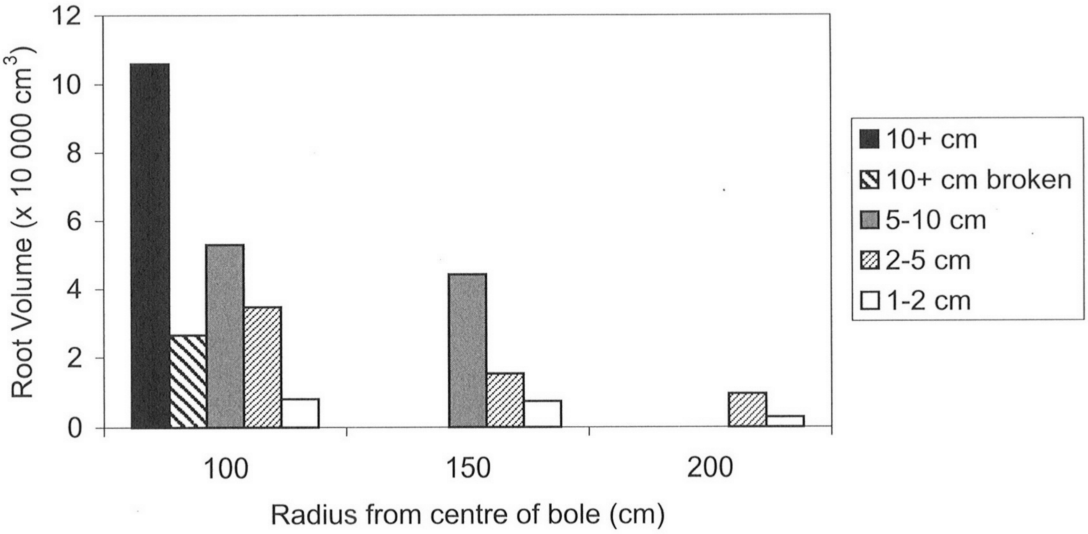
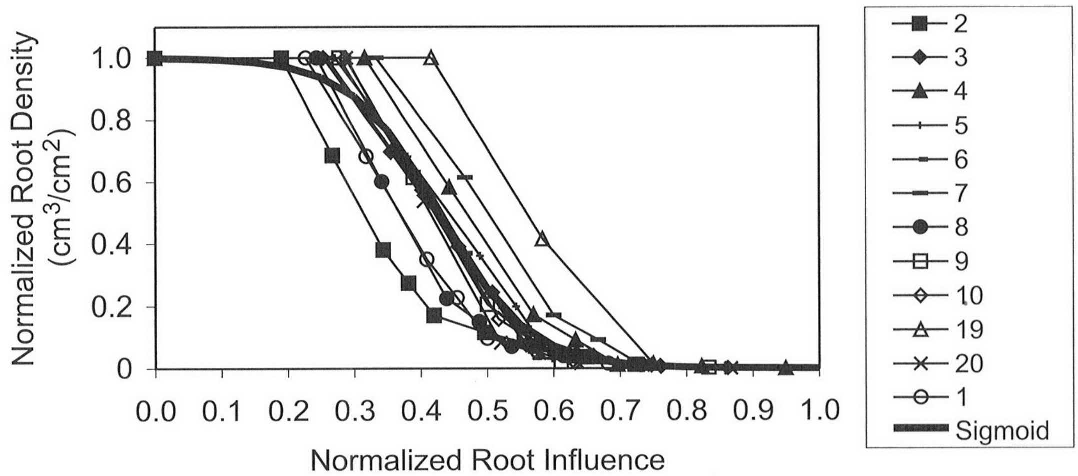


Fig. 3. Normalized root distribution for immature root systems 28–65 years old. The legend gives the sample number.



tric ring of the inventoried root system. Ages of tree boles were determined with an increment corer and counting of annual growth. No trees younger than 28 years were found with exposed root systems.

Data analysis

Root inventories were analysed to generate spatially distributed estimates (Fig. 2). It was assumed that the roots were circular in cross section and that the tortuosity was equal to unity in each concentric section; thus, each inventoried root cylinder was assumed to be 50 cm in length. The roots around the bole were assumed to stretch from the edge of the solid root mass to the intersection with the roots inventoried at 100 cm from the centre of the bole (Fig. 2).

To simulate root cohesion, we needed relationships to describe the root volume distribution and the radius of rooting extent of the root system. The derivation of a spatial relationship that applies to a population of root systems requires both the distance from the bole and the root volume be normalized. The root volumes in each 50-cm concentric ring were first converted to root densities by dividing by the soil surface area within each respective incremental concentric ring. The root densities in each incremental ring were normalized by the maximum density. The density of the centre was set equal to the maximum, as a density cannot be calculated without an area and it is reasonable to estimate that the maximum density is under the bole (Eis 1987).

The root influence radius was defined as the radius at which the root density dropped by 99%; for the 20 inventoried root systems, this relationship is

$$[1] \qquad \mathrm{RIR} = 2.1376 \times \mathrm{Age} + 109.52$$

where RIR is the root influence radius (cm) and Age is the age of the tree (years). The R^2 value for this relationship is 0.77. Comparing normalized root densities with normalized root influence radii, the data fit reasonably well into two tree age groups separated by a 23-year age gap where no root systems were sampled: 28–65 years (Fig. 3) and 88–110 years (Fig. 4). The numbers in the legends of both of these figures refer to the root system identification number. The normalized root density functions are sigmoidal in shape and can be described by

$$[2] \qquad \mathrm{NRD} = 1 - [a + b \times \exp(-k \times \mathrm{NRI} \times 100)]^{-1}$$

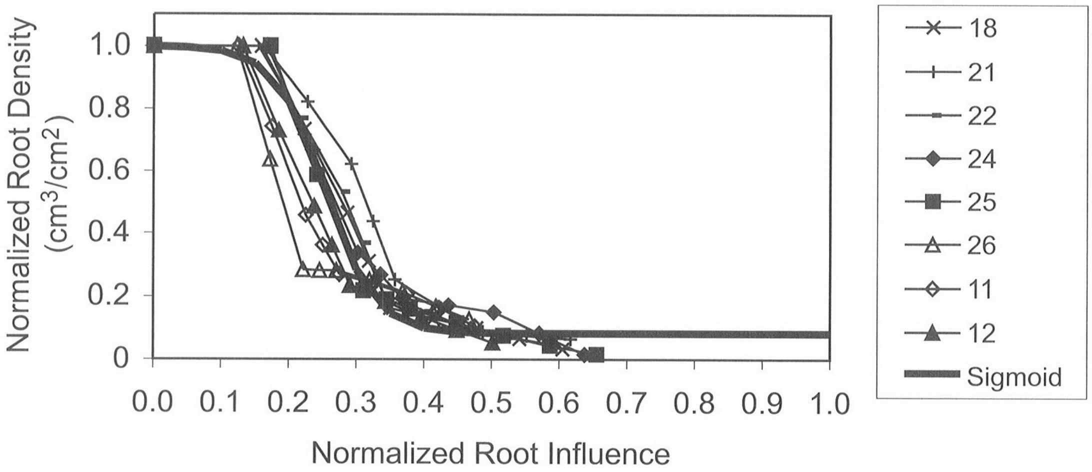


Fig. 4. Normalized root distribution for mature root systems 88–110 years old. The legend gives the sample number.

Fig. 5. Root cohesion values in a 79-year-old forest of 400 stems/ha; spatially averaged ΔC = 4.36 kPa. Minimum intertree spacing is 2.5 m. Darker colours indicate areas of higher root cohesion.

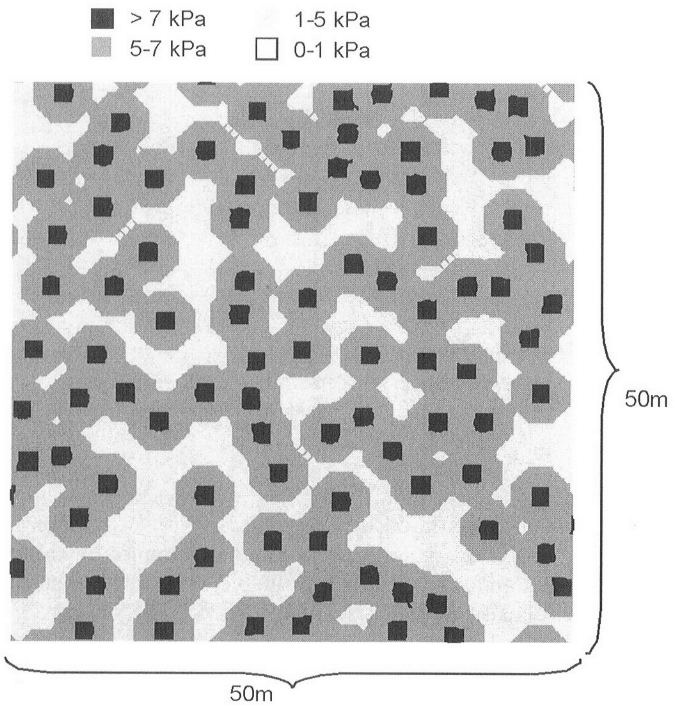
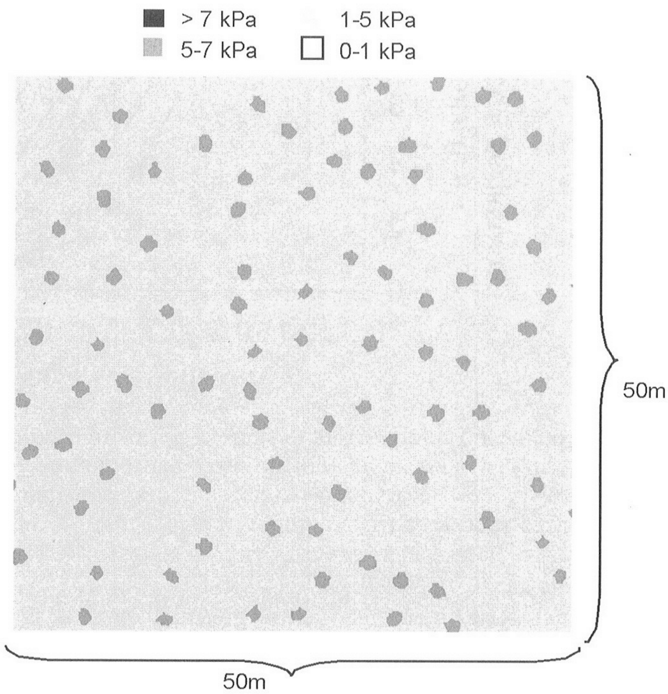


Fig. 6. Root cohesion values in a 90-year-old forest, 10 years after clear-cut harvesting; spatially averaged ΔC = 1.80 kPa. Current tree density is 2000 stems/ha with 10-year-old planted trees surrounding recently harvested tree locations. Minimum intertree spacing is 2.5 m. Darker colours indicate areas of higher root cohesion.



where NRD is the normalized root density; a, b, and k are empirical coefficients; and NRI is the normalized root influence radius. The values of the empirical coefficients for both tree age groups are based on ocular best fitting of eq. 2 and have values of 1, 625, and 0.15, respectively, for the younger group and 1.09, 1000, and 0.22, respectively, for the older trees. Combining eqs. 1 and 2, the normalized root density can be estimated for a given distance (centimetres) from the bole of a tree of a given age. The horizontal root density distribution is assumed to represent the horizontal distribution of root cohesion, which follows from Ziemer (1981), where increases in the soil strength resulted from increases in root biomass.

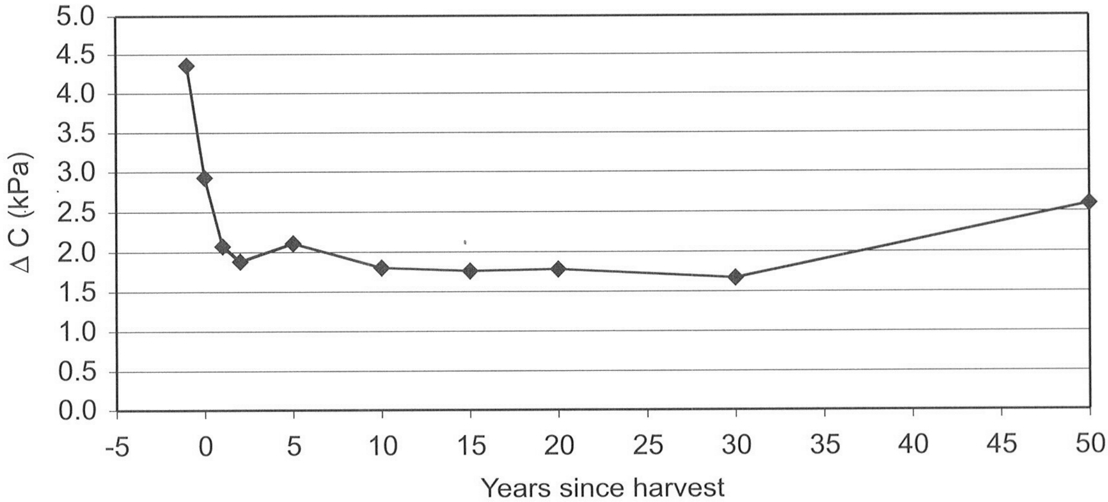
Results and discussion

A Douglas-fir forest stand was subjected to a variety of forest management scenarios. For all scenarios, the same random tree positions were used to allow better comparison of results. The following scenarios were simulated:

(1) Initial condition

A 79-year-old stand with a density of 400 stems/ha. Minimum spacing was set at 2.5 m; no harvesting was simulated. The output from the model displays the root cohesion sur-

Fig. 7. Spatially averaged simulated root cohesion conditions during a 50-year period following clear-cut harvesting (Scenario 2).



face (Fig. 5). High values of simulated root cohesion occur under the boles of the trees as well as among individual root systems in areas where two or more systems overlap. Areas of low root cohesion are found where trees are more widely spaced, but such areas are generally not extensive, and the total area of low root cohesion on the slope is small. Because of no recent harvesting in this site, the minimum root cohesion is 1.5 kPa, representing the understory root component. The average value of root cohesion for the 0.25-ha area is 4.36 kPa.

(2) Initial conditions with clear-cut harvesting

Clear-cutting occurs when the forest becomes 80 years old. The spatial distribution of root cohesion is displayed at 10 years after harvesting (Fig. 6), and spatially averaged values simulated at 1, 2, 3, 5, 10, 15, 20, 30, and 50 years after harvesting are shown in Fig. 7. Much of the simulated area has reduced root cohesion because of the decay of the large tree roots. The influence of planted seedlings is visible; regenerating root systems cause the uneven rings of root cohesion but are not yet more prominent then the decaying root systems of the clear-cut trees. The establishing root systems are also limited in their extent of influence and thus only span between proximate zones of elevated root cohesion. Thus, in unstable terrain, most of this site would be susceptible to landslides at this time. Spatially averaged root cohesion rapidly declines during the first 3 years followed by a minor recovery in year 5 (Fig. 7). Subsequently, root cohesion decreases slightly until year 30, after which time, gradual recovery occurs as regenerating trees develop their root systems. The initial decline is due to the onset of decay in the tree root systems and the elimination of the understory root cohesion component. The small recovery at 5 years can be attributed to the full reestablishment of the understory root cohesion (1.5 kPa). The decline between 20 and 30 years is the result of the thinning of immature trees back to the preharvest density. At 50 years, root cohesion recovery is well underway. The recovery period is longer than in other models describing temporal variations in root cohesion as a result of forest harvesting (Sidle 1991, 1992). The sustained depression of root cohesion is attributable to the physical data regarding root systems. The young root systems examined had much smaller root volumes and less radial rooting extent than did the older trees; no root systems <28 years old were examined. The linear relationship given in eq. 1 may not be appropriate for trees <28 years old and could explain the difference between the model output and other reported recovery curves. Also, Schmidt et al. (2001) found that certain 100-year-old industrial forests had species compositions, lateral root cohesion, and root diameters that more closely approximated younger clearcuts than natural forests. In our study, all of the trees 45 years and younger were located in areas that could be considered industrial forests. Further work is needed to describe these young root systems, especially because they are very important during the initial recovery period for root cohesion following harvesting.

(3) Initial conditions with selection cut harvesting

Every 20 years, a random selection of 25% of the trees older than 60 years are harvested. The spatial distribution of root cohesion is displayed immediately following the 10th entry, 200 years after the first harvest (Fig. 8). The influence of four very large trees on root cohesion is evident; these older trees significantly raise the spatially averaged root cohesion (3.55 kPa) for the slope. The model may not be correctly simulating the root cohesion contributions of these older trees because the maximum age of sampled root systems was 110 years. Further work could focus on describing these older root systems; however, their impact on slope stability is likely less important than the influence of the young trees. The influence of intermediate trees as well as decaying root systems is also evident. The understory has been recently disturbed (contributing 0 kPa) but will recover fully in 5 years (1.5 kPa). Moderate-sized contiguous areas of the hillslope (~200 m^2) with low cohesion values exist in this simulation; thus, the potential for small landslide occurrence exists.

(4) Initial conditions with strip-cutting

Every 20 years, 5-m cut strips are harvested and 15-m leave strips remain. The spatial distribution of root cohesion is displayed immediately following the 10th entry, 200 years after the initial harvest (Fig. 9). Successively to the right of

Table 1. Comparison of root cohesion simulations.

Forest age (years)	Tree age (years)	Density (stems/ha)	Harvest type	Average slope root cohesion	Original root cohesion (%)
79	79	400	No harvest	4.36	100
80	0	2000	Clear-cut	2.93	67
81	1	2000	Clear-cut	2.07	47
82	2	2000	Clear-cut	1.88	43
85	5	2000	Clear-cut	2.11	48
87	7	2000	Clear-cut	1.92	44
90	10	2000	Clear-cut	1.80	41
95	15	2000	Clear-cut	1.76	40
100	20	400	Clear-cut	1.78	41
110	30	400	Clear-cut	1.67	38
130	50	400	Clear-cut	2.59	59
280	Mixed	800	Selection cut	3.55	81
280	Mixed	800	Strip-cut	2.51	58

Note: Forest age is the time since the simulation was initiated. Tree age is the time since the last harvest for clear-cuts; for selection cutting and strip-cutting, the trees are of mixed age. Average root cohesion is for the simulated 0.25-ha slope. Percentage of original root cohesion is relative to the 79-year-old Douglas-fir forest of 400 stems/ha.

Fig. 8. Root cohesion values in a forest of mixed age managed by selection cutting, 200 years after the first harvest; ΔC = 3.55 kPa. Current tree density is 800 stems/ha with 10-year-old planted trees surrounding recently harvested tree locations. Minimum intertree spacing is 2.5 m. Darker colours indicate areas of higher root cohesion.

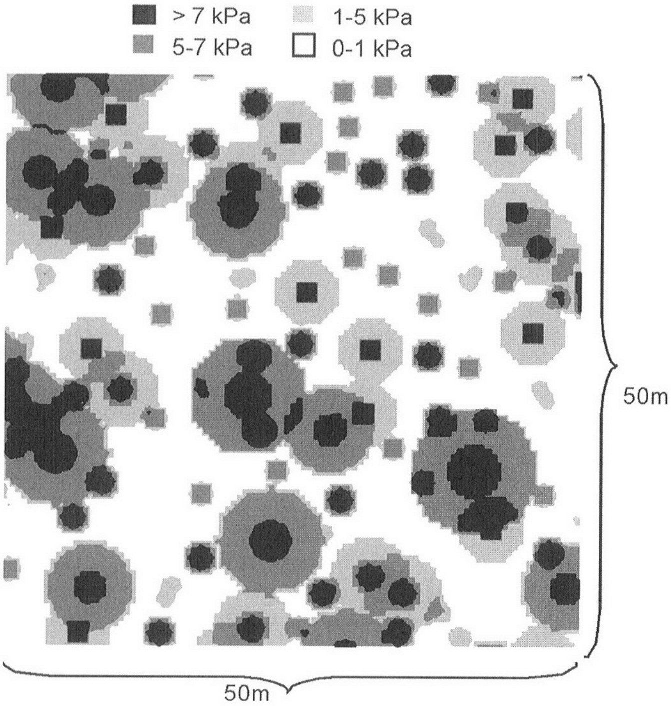
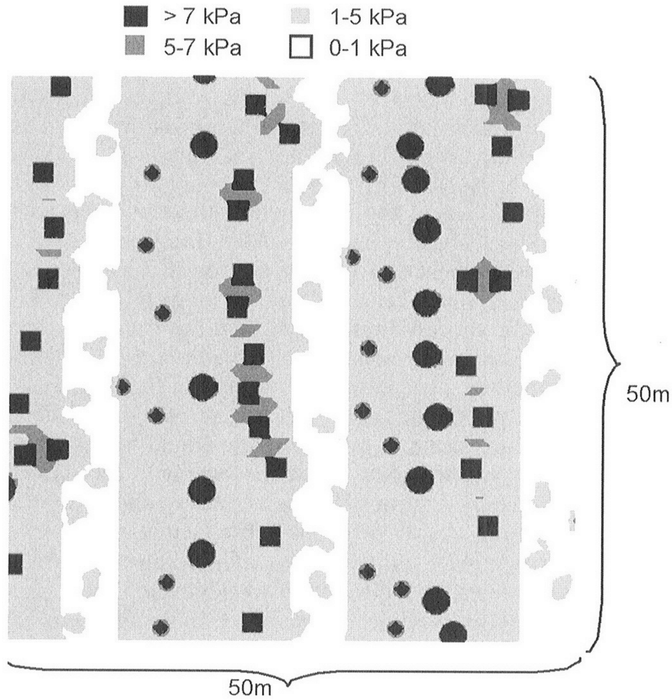


Fig. 9. Root cohesion values in a forest of mixed age managed by strip-cutting, 200 years into scenario; ΔC = 2.51 kPa. Current tree density is approximately 1000 stems/ha with 10-year-old planted trees surrounding recently harvested tree locations. Minimum intertree spacing is 2.5 m. Darker colours indicate areas of higher root cohesion.



the recently harvested strips lie the previously harvested areas with trees of age 20, 40, and 60 years old, respectively. The disturbance of the understory is noticeable in the recently harvested strips, and recovery is apparent in the remaining strips. This harvesting system decreases the regions of reduced root cohesion by limiting the disturbed area, and the narrow cut strips allow for overlapping contributions from live neighbouring root systems. This influence could be maximized by not harvesting adjacent strips in successive entries.

The simulated results clearly show that forest harvesting affects root cohesion (Table 1), agreeing with empirical studies (e.g., Bishop and Stevens 1964; Endo and Tsuruta 1969; O'Loughlin and Pearce 1976). The partial cutting scenarios have higher values of spatially averaged root cohesion compared with the clear-cutting scenarios because of the retention of live root systems. The model allows for the visualization of spatial patterns of root cohesion. A pattern evident in all simulations was the bridging among trees where their root systems overlapped; this produced regions of accentuated root cohesion via the summation of the component root systems. Modeling root systems independently likely underestimates the resultant cohesion because there is no provision for including the connectivity and overlap of multiple root systems. A temporal pattern of root cohesion inherent in each tree, but that becomes more prominent when considering the spatially distributed network, is the rapid decline of root cohesion following harvesting.

Many parameters affect the root cohesion at a particular location, including tree species, stand density, vigour, and age, soil fertility, soil drainage, and other site conditions. Further, the method of measuring root cohesion can influence the value obtained. Data collected from spatially limited areas, such as soil pits (Burroughs and Thomas 1977) or in situ shear box tests (e.g., Abe and Iwamoto 1986; Ekanayake et al. 1997), provide information on the root cohesion conditions at one location on the slope; these results become less reliable when extrapolated. Values derived from back-calculations also suffer from spatial confinement (e.g., Sidle and Swanston 1982), i.e., values obtained at the location of a landslide may not be representative of the conditions on the rest of the slope. In this model, we used conditions that were typical of Douglas-fir stands to increase the chances that future studies may more rigorously test the model. Douglas-fir is planted in many intensely managed forests in the Pacific Northwest and is one of the most investigated tree species in terms of rooting cohesion and distribution. Unfortunately, a majority of the root systems investigated were on gently sloping terrain; few windthrown trees were found in steep terrain. While operational feasibility was not a prime consideration during the development of the model, an attempt was made to display the effects of different silvicultural systems on root cohesion. Narrow strip-cuts on steep ground appear feasible, although this technique is not widely used; single-tree selection cutting methods are known to be used on the coast of British Columbia (Cleaver 2001).

Summary

A computational model was developed that utilized field data on root size distribution together with a root decay relationship (Sidle 1991) to simulate the spatial and temporal variability in root cohesion in a forested hillslope. Simulated results of typical harvesting and silvicultural treatments indicate potential short- and long-term trends in root cohesion. Selection cutting maintained the highest spatially averaged root cohesion (3.55 kPa), while strip-cutting maintained 2.51 kPa. Clear-cutting produced the greatest decline in root cohesion, from 4.36 kPa before harvesting to a minimum of 1.67 kPa 30 years after harvesting. It is highly beneficial to the maintenance of root cohesion to retain living root systems, including understory species. Although the selection and strip-cutting scenarios had areas of reduced root cohesion, the spatial extents were much smaller than in the clear-cuts. These findings imply that clear-cutting could increase the numbers of landslides as well as the probability of larger landslides, whereas partial cutting may affect a lesser increase on small landslides. It is intended that aspects of this model be applied to slope stability modeling so the character of the root cohesion parameter can be more adequately represented.

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