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Forest soil disturbance intervals inferred from soil charcoal radiocarbon dates

Daniel G. Gavin

Abstract: Forest soil disturbance intervals are usually too long to measure using plot-based studies, and thus they are poorly understood. The mean soil disturbance interval (MSDI) in an old-growth forest on the west coast of Vancouver Island was estimated from radiocarbon dates of charcoal from organic and mineral soil horizons. Two assumptions are required to estimate the MSDI: (1) charcoal from forest fires is deposited within the organic horizon and eventually mixed into deeper mineral horizons by soil disturbances, and (2) the probability of soil disturbance is spatially homogeneous and affected only by the time since the last fire or the last soil disturbance. The MSDI is then estimated by the rate at which the proportion of undisturbed sample sites (determined by the proportion of sites with charcoal from the most recent fire in the organic horizon) decreases with increasing time since the last fire. Soil charcoal evidence of time since fire was determined at 83 sites using 141 radiocarbon dates. The estimated MSDI was greater on slopes (ca. 2010 years) than on terraces (ca. 920 years). The long periods between soil disturbances, especially on slopes, are consistent with other evidence from the study area that suggests infrequent tree uprooting is the predominant mode of soil disturbance.

Résumé : Les intervalles entre les perturbations du sol en forêt sont habituellement trop longs pour être mesurés à l'aide de parcelles échantillons et sont par conséquent peu connus. L'intervalle moyen entre les perturbations du sol dans une forêt ancienne de la côte ouest de l'île de Vancouver a été estimé en ayant recours à la datation au carbone du charbon de bois présent dans les horizons organique et minéral du sol. On doit faire deux hypothèses pour estimer l'intervalle moyen entre les perturbations du sol : (1) le charbon de bois produit par les feux de forêt est déposé dans l'horizon organique et éventuellement incorporé plus profondément dans l'horizon minéral par les perturbations du sol et (2) la probabilité associée à une perturbation du sol est homogène dans l'espace et affectée uniquement par le temps écoulé depuis le dernier feu ou la dernière perturbation du sol. L'intervalle moyen entre les perturbations est ensuite estimé en utilisant le taux de diminution de la proportion de stations non perturbées (déterminé par la proportion des stations échantillonnées où du charbon de bois provenant du plus récent feu est présent dans l'horizon organique) en fonction du temps écoulé depuis le dernier feu. Le temps écoulé depuis un feu sur la base du charbon de bois présent dans le sol a été déterminé dans 83 stations à l'aide de 141 datations au carbone. L'intervalle moyen estimé entre les perturbations du sol est plus long sur les pentes (ca. 2010 ans) que sur les terrasses (ca. 920 ans). Les longues périodes entre les perturbations du sol, particulièrement sur les pentes, sont consistantes avec les autres indices observés dans la zone d'étude indiquant que le déracinement peu fréquent des arbres est le mode prédominant de perturbation du sol.

[Traduit par la Rédaction]

Introduction

The mixing of forest soil horizons is an important geomorphological and ecological process, though little is known about the frequency of soil disturbance events. There are many modes of forest soil disturbance, including tree uprooting by windthrow, bioturbation by earthworms or vertebrates, and freeze–thaw processes (Schaetzl at al. 1990; Carcaillet 2001). Tree uprooting may mix soil horizons and result in a characteristic pit-and-mound microtopography that persists for decades to centuries (Stephens 1956; Beatty and Stone 1986; Bormann et al. 1995). Likewise, bioturbation by earthworms and burrowing animals, cryoturbation, and landslides may homogenize surface soil horizons, and these modes of disturbance also vary among habitats and landforms (Paton et al. 1995; Jakob 2000). For all modes of soil disturbance, however, soil disturbance intervals are too long to measure using plot-based studies.

In this study, I estimate the mean soil disturbance interval using a large set of radiocarbon dates of soil charcoal from a coastal temperate rainforest on Vancouver Island, British Columbia, Canada. These radiocarbon dates were previously analyzed for a fire-history study, but not with respect to soil disturbance (Lertzman et al. 2002; Gavin et al. 2003*a*, 2003*b*). Using assumptions about how charcoal is incorpo-

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rated into mineral horizons of soil and a simple statistical model, the mean soil disturbance interval can be calculated from the distribution of charcoal ages in organic versus mineral horizons over a set of sample sites. I use this method to compare the soil disturbance intervals between terrace and slope landforms.

Materials and methods

Assumptions and model

The method used here requires Podzol soils with a distinct boundary between organic (O) and mineral (E and B) horizons. To estimate the mean soil disturbance interval (MSDI), I used a statistical model that requires two assumptions. First, I assume that the vast majority of charcoal is initially deposited above the mineral horizon, and that soil disturbance is required to mix charcoal into the mineral horizon (Fig. 1). For example, a field survey has shown that fire may consume organic soils and deposit considerable amounts of charcoal above the mineral horizon (Ohlson and Tryterud 2000). Experiments have also indicated that charcoal is unlikely to form within a mineral soil horizon with high moisture content (Frandsen 1987). Thus, charcoal in mineral horizons is likely a result of soil mixing. This assumption agrees with similar models of Podzol disturbance and redevelopment (Armson and Fessenden 1973; Vasenev and Targul'yan 1995).

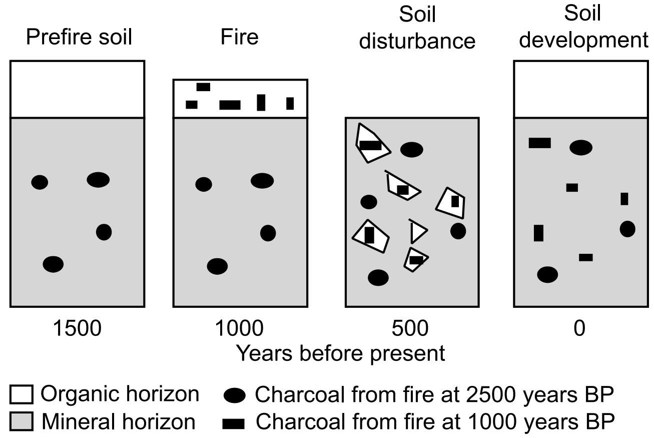
Second, I assume that soil disturbance is a spatially and temporally homogeneous process, as proposed by Norton (1989). Thus, this method is only applicable in topographic settings where uprooting and other modes of soil disturbance occur with a spatially uniform probability (e.g., sheltered valley bottoms; Kramer et al. 2001). The model does acknowledge that the probability of soil disturbance may be a function of the time since the last soil disturbance or the time since the last fire. For example, following tree uprooting or death by fire, a century or more may be required for regenerating trees to reach a size susceptible to another windthrow. In contrast, the spatial and temporal pattern of fire may be nonrandom with no effect on the model results.

With these assumptions, the age distribution of undisturbed soil ($A(t)$) can be modeled using the Weibull distribution as applied to fire-history studies (Johnson and van Wagner 1985; Huggard and Arsenault 1999):

$$[1] \qquad A(t) = \exp[-(t/b)^c]$$

where $A(t)$ is the proportion of sites that have not experienced soil disturbance for t years (i.e., the proportion of sites with a time since fire of t years that have charcoal in the organic horizon), b is the exponential decay parameter, and c controls the shape of the distribution. When $c = 1$ the model is identical to the negative exponential model, when $c > 1$ the probability of disturbance increases with time since the last disturbance, and when $c < 1$ the probability of disturbance decreases with time since the last disturbance. MSDI is calculated as $b\Gamma[(1/c) + 1]$, where Γ is the gamma distribution. Confidence intervals of $A(t)$ and MSDI may be calculated from bootstrap resampling of the sample sites. Estimates of $A(t)$ are more robust for recent than for older time-since-fire age-classes because the number of sites used to compute $A(t)$ decreases with increasing time since fire. Therefore, I fit the Weibull model using a nonlinear regression in which the squared residuals for each 200-year age-class are weighted by the number of sites contributing to the estimate of $A(t)$ in that age-class.

Fig. 1. Schematic showing the assumption of how charcoal is transported from organic to mineral horizons in Podzols. Charcoal from a fire at 1000 years before present (BP) is deposited in the organic horizon and mixed into the mineral soil at 500 years BP. A new charcoal-free organic horizon has developed by 0 years BP.

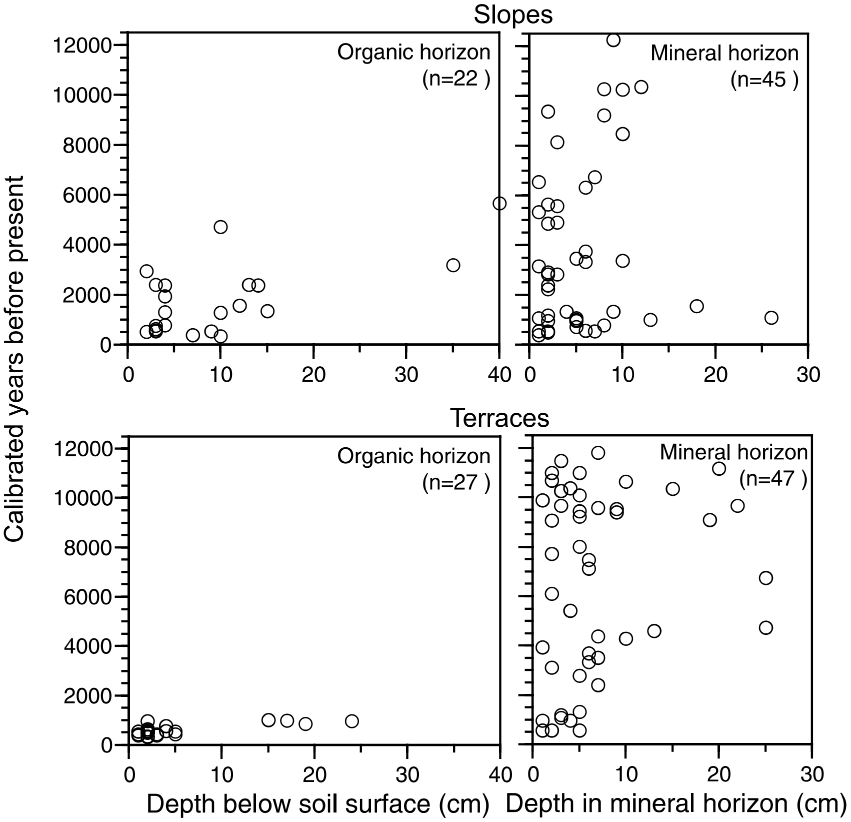


Study area and sampling

Sampling was conducted in the lower elevations (<200 m) of the Clayoquot River watershed, located 20 km from the Pacific coast of Vancouver Island (49°15′N, 125°25′W). The Clayoquot Valley is a north–south trending valley bordered by high ridges (>1200 m elevation) and sheltered from the direct winds of the storms from the southeast (Pearson 2001). The terrain is composed of level terraces that abut sharply with steep (40% to >60%) slopes. Forests are dominated by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn ex D. Don) with Pacific silver fir (*Abies amabilis* (Dougl. ex Loud.) Dougl. ex J. Forbes) and Sitka spruce (*Picea sitchensis* (Bong) Carrière) also common. Soils are Ferro-Humic Podzols, with a well-defined organic mor (O) horizon overlying a weathered mineral (Bs and Bhs) horizon (Jungen 1985). The E horizon was very thin at most sites. Thus, horizons could be diagnosed easily at a coarse level (O vs. B) in the field. Only 8% of the sites appeared to contain a recently mixed or transitional A horizon, which I treated as a mineral horizon in subsequent analyses.

Soil charcoal sampling was conducted as part of a fire-history study and designed to maximize the probability of detecting the most recent fire (Gavin et al. 2003*a*). Sample sites were spaced 150–400 m apart and located on locally level terrain that was not affected by down-slope soil movement and where charcoal is most likely to accumulate (Bassini and Becker 1990). In the field, I searched the organic horizon, where charcoal from the most recent fire is most likely to be located, from at least three 5 cm diameter soil cores at each site. In the laboratory, I carefully sieved an additional three to five soil cores from each site and searched for charcoal in the large fraction (>0.5 mm) under × 10 magnification. The uppermost piece of charcoal at

Fig. 2. Depth–age relationship of the 141 radiocarbon-dated charcoal fragments used in this study.



each site was submitted for radiocarbon dating at Lawrence Livermore National Laboratory (Livermore, Calif.). Additional dates were obtained from several sites, especially if (1) there appeared to be a stratigraphy of charcoal in the organic horizon, or (2) if charcoal was found only in the mineral horizons.

A total of 141 accelerator mass spectrometry radiocarbon dates were obtained, of which 73% were based on a single piece of charcoal (usually >5 mm in length); the remaining dates were based on multiple pieces (0.5–2 mm in length) from the same depth in the soil. It is not likely that the dates based on multiple pieces are the average of multiple fires, because dates of single pieces of charcoal from the same site yielded a similar age (<300-year difference) in 17 of 35 comparisons, and dates from the same depth were the same in 7 of 9 comparisons (Gavin et al. 2003*a*). Also, because charcoal in the organic horizon was always younger than that in the mineral horizon, it was possible to estimate that the most recent fire was dated at more than 90% of the sites (Gavin et al. 2003*a*).

All radiocarbon dates were converted to calibrated years before present (years BP) (Stuiver et al. 1998). Tree-ring evidence of fire was used as a more accurate method of dating surficial soil charcoal at the 18 sites where there was stand-structural evidence of fire (Gavin 2001; Gavin et al. 2003*a*). The youngest radiocarbon date or tree-ring date at each site was used to determine the time since fire. The proportion of sites with charcoal in the organic horizon for each 200-year time-since-fire class was determined separately for sites on slopes and sites on terraces. Complete lists of radiocarbon dates are available in Gavin (2001) (26 dates), Gavin et al. (2003*a*) (120 dates, 5 dates are reported in both studies[1]), and Gavin et al. (2003*b*) (47 dates, all also in Gavin et al. 2003*a*). These dates are also summarized in Lertzman et al. (2002); that study included seven additional dates from two subalpine forest sites unrepresentative of the remainder of sites in the study area.

Results and discussion

Charcoal ages in the organic horizon are usually less than 3000 years, but charcoal ages in the mineral horizons span the last 12 000 years (Fig. 2). The observed difference in the maximum age of charcoal in the organic horizon and mineral horizon is consistent with the assumption that charcoal is mixed into mineral horizons at some time after being deposited in the organic horizon. The maximum age of charcoal in the mineral horizon (12 200 years, shortly postdating deglaciation) indicates that charcoal is well preserved in these soils. Another study with these dates showed that charcoal abundance is only very weakly related with the time since fire (Gavin et al. 2003*a*), suggesting that charcoal is lost at a slow rate from fragmentation.

A weak relationship between charcoal age and depth occurred in the organic horizon on slopes (r = 0.638, P = 0.001) and terraces (r = 0.739, $P < 0.0001$) though no age–depth relationship occurred in the mineral horizon (r = 0.106, P = 0.490 for slopes; r = 0.194, P = 0.192 for terraces; Fig. 2). Organic horizons are likely accumulating with time, as would be expected for Cumulic mor humus horizons

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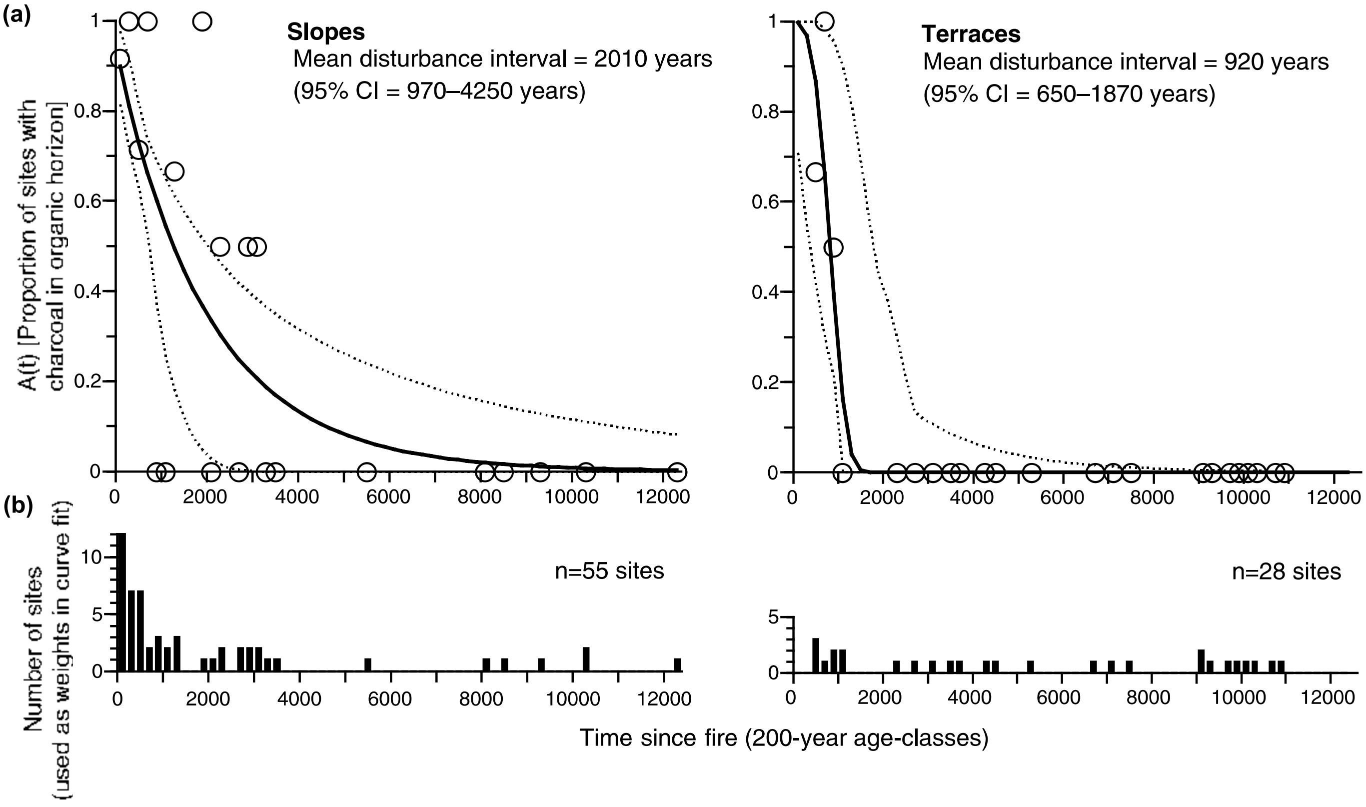
[1] Available online at http://www.esapubs.org/archive/ecol/E084/004/default.htm.

Fig. 3. Calculations of mean soil disturbance intervals on slope and terrace landforms. (*a*) Proportion of sites with soil not disturbed since the last fire, as determined by charcoal from the most recent fire remaining in the organic horizon. The 95% confidence intervals of the fitted Weibull curve and the mean disturbance interval are based on 500 bootstrap samples of the sample sites. (*b*) The number of sites in each 200-year age-class (the time-since-fire distribution) used to compute *A*(*t*) and also used as weights in the Weibull curve fit. The exceptionally long time since fire at some sites is the focus of earlier papers (Lertzman et al. 2002; Gavin et al. 2003*a*).



(Cruikshank and Cruikshank 1981), but have a maximum age of ca. 6000 years on slopes and only ca. 1000 years on terraces. In contrast, mineral horizons appear to be mixed, resulting in no age–depth relationships within or among sites (Lertzman et al. 2002).

The Weibull curve fit to the age distribution of the proportion of undisturbed soil was better on terraces than on slopes (weighted r^2 = 0.87 and 0.72, respectively; Fig. 3). On terraces, *A*(*t*) declined rapidly and was best fit with a platykurtic Weibull curve (c = 3.65), indicating the probability of disturbance increases with time since the last disturbance. On slopes, *A*(*t*) declined gradually and was best fit with a Weibull curve that was indistinguishable from a negative exponential curve (c = 0.97), indicating the probability of disturbance is independent of the time since the last disturbance. The mean soil disturbance interval (MSDI) computed from each Weibull curve was greater on slopes (2010 years) than on terraces (920 years), though each MSDI estimate had large confidence intervals (Fig. 3).

Estimates of MSDI on both terraces and slopes are longer than previously estimated rates of soil disturbance in conifer forests (Jonsson and Dynesius 1993; Vasenev and Targul'yan 1995; Kramer et al. 2001). One cause of the long MSDI may be that tree uprooting is rare in the study area. Other studies from this area support this observation. Historical aerial photographs (1939 to 1988) showed no evidence of windthrow at low elevations in this watershed, likely because the Clayoquot Valley is not directly exposed to onshore winds (Pearson 2001). In addition, a canopy gap survey in an adjacent watershed found that only 20% of tree deaths involved uprooting (Lertzman et al. 1996). Combined with an estimated mean canopy tree turnover rate of 350–950 years (Lertzman et al. 1996), the tree-uprooting interval is likely to be on the scale of millennia.

A second cause of the long MSDI may be that modes of soil disturbance other than tree uprooting, including landslides, cryoturbation, and bioturbation, are extremely rare in the study area. First, landslides are restricted to steeper slopes than those sampled and are very infrequent in watersheds such as the Clayoquot Valley that are >15 km from the coast (Jakob 2000). Second, in subalpine meadow soils, freeze–thaw processes and animal burrowing are important mechanisms to fragment charcoal and move it into the mineral horizon (Carcaillet 2001). However, in the Clayoquot Valley study area soils do not freeze owing to mild winters (January mean temperature = 4 °C). It is also likely that bioturbation is rare because these soils are wet and very acidic, creating poor conditions for earthworms (Curry 1998) and other invertebrates (Paton et al. 1995). During four summers of field sampling, soils never displayed evidence of bioturbation by burrowing animals, and earthworms were encountered very rarely.

The difference in MSDI between terraces and slopes is consistent with tree uprooting as the dominant form of soil disturbance in the Clayoquot Valley. On terraces, trees are rooted in deep colluvium, reach greater heights than on slopes (>45 m), and may create large tip-up root plates when windthrown, thus disturbing large areas of soil. Terraces also have more evidence of pit-and-mound features than slopes, consistent with their shorter MSDI. On slopes, the very long MSDI may be partly due to smaller root plates and less frequent windthrow overall. For example, western redcedar, a species that does not create large root plates when uprooted (Pearson 2001), is more common on slopes than terraces. The difference in MSDI is also consistent with lower productivity on slopes (mainly cedar and hemlock forests) than terraces (mainly hemlock and fir forest) that in similar forests, has been attributed to the long-term beneficial effects of tree uprooting on soil properties (Keenan et al. 1994; Bormann et al. 1995; Kramer et al. 2001).

Conclusions

An extensive set of soil charcoal radiocarbon dates from Podzols in old-growth forest support the assumption that periodic soil disturbances are required to move charcoal from organic into mineral horizons. With an additional assumption that such severe soil disturbances occur as a spatially and temporally homogeneous process, it is possible to fit a simple model to charcoal radiocarbon dates to compute the mean soil disturbance interval. This model had a strong fit with a set of 141 radiocarbon dates ($r^2 > 0.7$) and estimated mean soil disturbances intervals to be 920 years on terraces and 2010 years on slopes. Other evidence from the study site suggests that infrequent tree uprooting is responsible for these long soil disturbance intervals.

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References

Armson, R.A., and Fessenden, R.J. 1973. Forest windthrows and their influence on soil morphology. Soil Sci. Soc. Am. Proc. **37**: 781–783.

Bassini, F., and Becker, P. 1990. Charcoal's occurrence in soil depends on topography in Terra firme forest near Manaus, Brazil. Biotropica, **22**: 420–422.

Beatty, S.W., and Stone, E.L. 1986. The variety of soil microsites created by tree falls. Can. J. For. Res. **16**: 539–548.

Bormann, B.T., Spaltenstein, H., McClellan, M.H., Ugolini, F.C., Cromack, K., and Nay, S.M. 1995. Rapid soil development after windthrow disturbance in pristine forests. J. Ecol. **83**: 747–757.

Carcaillet, C. 2001. Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the European Alps based on AMS ^{14}C dates. Holocene, **11**: 231–242.

Cruikshank, J.G., and Cruikshank, M.M. 1981. The development of humus-iron podsol profiles, linked by radiocarbon dating and pollen analysis to vegetation history. Oikos, **36**: 238–257.

Curry, J.P. 1998. Factors affecting earthworm abundance in soils. *In* Earthworm ecology. *Edited by* C.A. Edwards. St. Lucie Press, Baton Rouge, La. pp. 37–64.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. **17**: 1540–1544.

Gavin, D.G. 2001. Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. Radiocarbon, **43**: 27–44.

Gavin, D.G., Brubaker, L.B., and Lertzman, K.P. 2003*a*. Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. Ecology, **84**: 186–201.

Gavin, D.G., Brubaker, L.B., and Lertzman, K.P. 2003*b*. An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Can. J. For. Res. **33**: 573–586.

Huggard, D.J., and Arsenault, A. 1999. Comment — Reverse cumulative standing age distributions in fire-frequency analysis. Can. J. For. Res. **29**: 1449–1456.

Jakob, M. 2000. The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. Catena, **28**: 279–300.

Johnson, E.A., and Van Wagner, C.E. 1985. The theory and use of two fire history models. Can. J. For. Res. **15**: 214–220.

Jonsson, B.G., and Dynesius, M. 1993. Uprooting in boreal spruce forests: long-term variation in disturbance rate. Can. J. For. Res. **23**: 2383–2388.

Jungen, J.R. 1985. Soils of southern Vancouver Island. British Columbia Surveys and Resource Mapping Branch, Ministry of Environment, Victoria, B.C.

Keenan, R.J., Messier, C., and Kimmins, J.P.H. 1994. Effects of clearcutting and soil mixing on soil properties and understory biomass in western red cedar and western hemlock forests on northern Vancouver Island, Canada. For. Ecol. Manage. **68**: 251.

Kramer, M.G., Hansen, A.J., Taper, M.L., and Kissinger, E.J. 2001. Abiotic controls on long-term windthrow disturbance and temperate rain forest dynamics in southeast Alaska. Ecology, **82**: 2749–2768.

Lertzman, K.P., Sutherland, G.D., Inselberg, A., and Saunders, S.C. 1996. Canopy gaps and the landscape mosaic in a coastal temperate rain forest. Ecology, **77**: 1254–1270.

Lertzman, K.P., Gavin, D.G., Hallett, D.J., Brubaker, L.B., Lepofsky, D., and Mathewes, R. 2002. Long-term fire regime from soil charcoal in coastal temperate rainforests. Conserv. Ecol. [serial online], **6**. Available from http://www.consecol.org/vol6/iss2/art5 [cited 1 March 2003].

Norton, D.A. 1989. Tree windthrow and forest soil turnover. Can. J. For. Res. **19**: 386–389.

Ohlson, M., and Tryterud, E. 2000. Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. Holocene, **10**: 519–525.

Paton, T.R., Humphreys, G.S., and Mitchell, P.B. 1995. Soils: a new global view. Yale University Press, New Haven, Conn.

Pearson, A.F. 2001. Patterns of wind disturbance in a coastal temperate rain forest watershed, Clayoquot Sound, British Columbia. *In* Windthrow Assessment and Management in British Columbia, Proceedings of the Windthrow Researchers Workshop, 31 January – 1 February 2001, Richmond, B.C. *Edited by* S.J. Mitchell and J. Rodney. British Columbia Forestry Continuing Studies Network, Vancouver, B.C. pp. 65–80.

Schaetzl, R.J., Burns, S.F., Small, T.W., and Johnson, D.L. 1990. Tree uprooting — review of types and patterns of soil disturbance. Phys. Geogr. **11**: 277–291.

Stephens, E.P. 1956. The uprooting of trees: a forest process. Soil Sci. Soc. Am. Proc. **20**: 113–116.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., Van der Plicht, J., and Spurk, M. 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon, **40**: 1041–1083.

Vasenev, I.I., and Targul'yan, V.O. 1995. A model for the development of sod-podzolic soils: by windthrow. Eurasian Soil Sci. **27**(10): 1–16.