Table 2. Estimated average sizes of paper birch at various rotation ages.

Stand age (years) and treatment	Height[1]	Diameter[2]
	Feet	*Inches*
20 years		
C	29.6	4.4
W	27.8	6.1
WFL	34.4	8.5
25 years		
C	37.0	5.5
W	34.8	7.7
WFL	43.0	10.7
30 years		
C	44.4	6.5
W	41.7	9.3
WFL	51.6	12.9

[1]*Based on rates of past 10 years.*
[2]*Based on rates of past 3 years.*

remembered that these birches were protected from deer browsing by fencing, which is essential in the early years if the benefits of brush control and fertilization are to be realized. Other attempts to establish paper birch plantations without protection from deer have not been successful (L. Safford, USDA Forest Service, Durham, New Hampshire, personal communication).

Given the growth of paper birch and its overall suitability to plantation management, I prepared estimates of heights and diameters after 20, 25, and 30 years (*table 2*). These estimates can be used as reasonable guides for management planning. The intended product would be high-quality sawlogs. As indicated earlier, heights would not be greatly affected by different management options. Paper birch trees receiving fertilizer and brush control should average over 50 feet in total height after 30 years. In addition, their average d.b.h. will be about 13 inches, or small sawlog size, so they could be harvested at that time. By comparison, planted trees without these treatments would probably require an additional 30 years to reach a comparable size.

The maximum stocking of paper birch that would not compromise these greater growth rates has not been determined in the field, but some estimates are possible. At a 20- by 20-foot spacing, this plantation began with 109 trees per acre. It is now obvious that crown closure is 10 or more years away, and closer spacing within the rows is clearly feasible. At a 20- by 10-foot spacing, there would be 218 trees per acre initially. If mortality after 30 years is 30 percent, about 153 trees per acre would remain. An average diameter of 12.9 inches would give a basal area of 139 square feet per acre. This value agrees with basal areas of fully stocked paper birch stands under natural conditions (Marquis et al. 1969). The difference is that natural stands with intensive thinning would require 90 years to reach the same mean stand diameter and basal area. ■

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Designing Stable Buffer Strips For Stream Protection

Ivars J. Steinblums, Henry A. Froehlich, and Joseph K. Lyons

ABSTRACT—On 40 streamside buffer strips in the Cascade Mountains of western Oregon, stability was a function of one vegetation and six topographic variables, and shading was related to three characteristics of buffer strips and one of adjacent clearcuts. Prediction equations were developed from these relationships to aid assessment of stream protection in proposed harvest designs and to aid rapid evaluation of design modifications. Options can be quantified so that the most suitable design may be chosen.

Buffer strips, uncut zones flanking streams within harvesting units, provide protection for stream ecosystems during and after timber harvest. The strips create shade (Brazier and Brown 1973), act as barriers to logging debris (Froehlich 1973), and help to stabilize stream banks by maintaining masses of living roots. Buffer strips must be properly designed to prevent failure and should be evaluated for effectiveness on a site-specific basis.

Failure of buffer strips is a frustrating, recurring problem. Wind is the major cause, and blowdown tends to be catastrophic. Damage from logging or disease may also occur. Regardless of the source of damage, debris from the strips can load stream channels when mobilized during high flows, posing a threat to downstream structures, deflecting flow into banks, and causing erosion. Conversely, debris can provide sediment storage areas in the channel, enhancing stability.

This article reports a study of environmental factors that affect buffer strip stability and stream shading.

Study Area

The 40 buffer strips evaluated in the study were on streams at elevations of 2,000 to 4,000 feet in the Cascade Mountains of western Oregon (*fig. 1*). Mean annual precipitation in the study area varies from 75 to 160 inches, increasing from south to north and with elevation. Prevailing winds are from the southwest during the winter, except at the northern end of the area where easterly foehn winds are common.

In the buffer strips at lower elevations, three tree species predominate: Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). At higher elevations, noble fir (*Abies procera*), white fir (*A. concolor*), grand fir (*A. grandis*), and Pacific silver fir (*A. amabilis*) grow along with the other species (Franklin 1979).

Volcanic activity followed by glaciation and erosion has sculpted the topography of the study area. Pyroclastic rocks, basalt, and andesite are the chief parent materials. Soils formed from pyroclastic are of silt to clay texture and are often poorly drained and subject to mass movement.

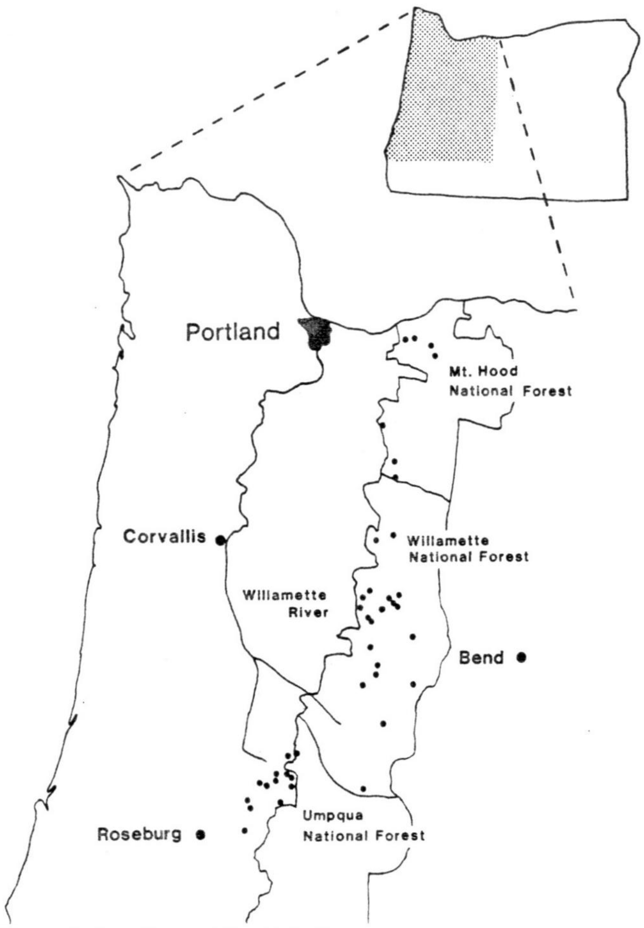

Figure 1. Locations of the 40 buffer strips studied in the Cascade Mountains of Oregon.

Basalt and andesite weather more slowly, producing soils with coarser texture, better drainage, and greater stability.

Measuring Vegetative and Topographic Variables

The buffer strips examined had been left as stream protection during logging from 1 to 15 years before the study began. No samples were taken where excessive blowdown had occurred and strips had been salvaged; therefore older strips in the sample tended to have a high degree of natural stability.

At each site, we sampled a 400- to 700-foot length of buffer strip, measuring strip width (WIDTH), streambank slope (SLPCRK), and direction of streamflow (ORIENT) at 100-foot intervals. Total height and diameter were measured for each tree within a strip, and each was classified by species and one of four conditions: standing live, standing dying, standing dead, and windthrown. The direction of damaging wind was determined from the orientation of windthrown trees.

We measured original gross timber volume and original gross basal area (ORIGBA) for each buffer strip, then subtracted the volume of windthrown timber from the original gross timber volume to determine volume remaining (VOLREM).

On the basis of understory species, each buffer strip was assigned to one of four moisture classes: very dry, modal, wet, or very wet. Original timber volume was multipled by moisture class number (for numbers see *table 1*) to get an interactive term (WETVOL). Each strip was also classified in the field in a natural stability group (STABRATE) —stable, moderately stable, or unstable—from visual estimates of indicators such as streambank cutting or failure, jackstrawed trees, large debris jams, swampy areas, and landslides.

To supplement the field observations, we used measurements from topographic maps and aerial photographs: slope of adjacent clearcut (SLPCC), elevation of buffer strip (ELEV), distance and difference in elevations between a strip and the nearest ridge in the direction of damaging winds (DISTRIDG, ELEVRIDG), and distance from a strip to uncut timber in the direction of damaging winds (DISTWIND).

Determining Shade Cover

Buffer-strip effectiveness was defined in terms of average stream shading during the period of minimum flow. Shading was quantified by estimating canopy density with an angular canopy densimeter. (For a discussion of the relation between shading, stream temperature, and angular canopy densimeter readings, see Brazier and Brown 1973.) An angular canopy densimeter is a 1-foot-square mirror divided into 16 3- by 3-inch squares and mounted on a 1.5-foot tripod.

Table 1. Moisture classes assigned each buffer strip and used in the interaction variable WETVOL.

Moisture class used in Equation 1	Understory species composition
1. Very dry	Salal, *Gaultheria shallon* Hazel, *Corylus* spp. Oregon grape, *Berberis nervosa* Ocean spray, *Holodiscus discolor*
2. Modal	Vanilla leaf, *Achlys triphylla* Dogwood, *Cornus* spp. Swordfern, *Polystichum munitum* Rhododendron, *Rhododendron* spp. Bracken fern, *Pteridium aquilinum* Vine maple, *Acer circinatum*
3. Wet	Red alder, *Alnus rubra* Coltsfoot, *Petasites frigidus* Lady fern, *Athyrium filix-femina* var. *californicum* Oxalis, *Oxalis oregana* Red huckleberry, *Vaccinium parvifolium*
4. Very wet	Skunk cabbage, *Lysichitum americanum* Sedges, *Carex* spp. Devil's club, *Oplopanax horridus* Salmonberry, *Rubus spectabilis*

The densimeter was placed in stream center, was oriented south, and was angled to reflect the canopy shading the stream during minimum flow. Angular canopy density (ACD) was an ocular estimate (in percent) of coverage of each of the 16 squares averaged for a given point. ACD was estimated at 100-foot intervals and averaged for each buffer strip. Twelve buffer strips were bounded with uncut areas to the south, so that ACD measurements for streams within those strips approximated undisturbed conditions.

Regression analysis was used to develop three predictive equations. Equation 1 relates buffer-strip stability, expressed as the percentage of timber volume remaining in a strip, to seven independent variables that describe the strip (*table 2*). Equation 2 relates ACD to buffer-strip width, and Equation 3 describes the relationship between ACD and one stand and two topographic variables.

Variables Related to Stability

Stability of the surveyed buffer strips ranged from 22 to 100 percent of the initial gross timber volume. Wind damage accounted for nearly 94 percent of volume loss; the remainder was due to logging damage, insects, and disease. Buffer strip stability was correlated with DISTWIND, ELEVRIDG, DISTRIDG, ORIENT, ELEV, STABRATE, and WETVOL. Equation 1 related the timber volume remaining in buffer strips (VOLREM) to these variables.

$$\begin{aligned} \text{VOLREM} &= 109.0 - 0.011\ \text{DISTWIND} \\ &+ 0.012\ \text{ELEVRIDG} \\ &+ 0.0023\ \text{DISTRIDG} + 7.55\ \text{ORIENT} \\ &- 0.0044\ \text{ELEV} \\ &- 4.48\ \text{STABRATE} - 0.032\ \text{WETVOL}. \quad (1) \\ R^2 &= 0.74 \end{aligned}$$

A significant relationship between buffer-strip width and stability was not apparent in the data. Nor was the age of a buffer strip significantly related to volume remaining. Apparently, volume susceptible to windthrow tends to be lost during the first few years of exposure.

Species composition of the buffer strip was an important component determining windthrow occurrence and amount. The percentage of windthrow of the sampled species differed significantly (*table 3*) when compared by a chi-square contingency test. Western redcedar was most windfirm, followed by western hemlock, Douglas-fir, and true firs (*table 3*). This finding agrees with that of Gratowski (1956) that western redcedar is the species least susceptible to windthrow in the H.J. Andrews Experimental Forest in western Oregon. However, Steinbrenner and Gessel (1956) ranked these species differently in southwest Washington, and Ruth and Yoder (1953) ranked them differently in the Oregon Coast Range. With the exception of the true firs, all tree species in our study were significantly less windfirm if individual trees were of greater than average height or diameter (*table 3*).

Table 2. Variables used to predict buffer strip stability (VOLREM) and shading (ACD).

Variable	Definition	Unit
VOLREM	*The measure of buffer strip stability in volume remaining after losses.*	*Percent of initial volume*
DISTWIND	The slope distance from the outer edge of the buffer strip to uncut timber in the direction of damaging winds.	Feet
ELEVRIDG	The change in elevation from the midpoint of the buffer strip to the top of the nearest major ridge in the direction of damaging winds.	Feet
DISTRIDG	The horizontal distance from the outer edge of the strip to the nearest major ridge in the direction of damaging winds.	Feet
ORIENT	Direction of streamflow: Compass azimuth (indicator variable). Westerly 180°–360° = 1 Easterly 0°–180° = 2	
ELEV	Elevation of the midpoint of the buffer strip above sea level.	Feet
STABRATE	Visual estimate of natural stability of the buffer strip (indicator variable). Stable = 1 Moderately stable = 2 Unstable = 3	
WETVOL	An interaction term multiplying the gross timber volume of the buffer strip immediately after timber harvest and moisture class. Based on understory indicator species.	
ACD	*Angular canopy density, the measure of buffer strip shading effectiveness. Indicated by shading of the stream at minimum flow.*	*Percent, as measured by an angular canopy densimeter*
WIDTH	Average width of buffer strip.	Feet
ORIGBA	Original basal area of the timber comprising the buffer strip.	Ft^2/acre gross
SLPCC	Slope of the clearcut adjacent to the buffer strip.	Percent
SLPCRK	Slope of the streambank within the buffer strip.	Percent

Table 3. Percentage of windthrow[1] of trees in 40 buffer strips, by species and size class.

Species	Av. height	Av. diameter	Above-av. height	Below-av. height	Above-av. diameter	Below-av. diameter	All trees of species[2]
	Feet	*Inches*			*Percent*		
Western redcedar	120	30	18	7	21	5	11
Western hemlock	110	20	20	14	19	14	17
Douglas-fir	180	40	27	13	25	17	22
True firs	130	20	51	57	48	69	54

[1]Percentage of the total volume of trees of a given species and size in all buffer strips.
[2]Percentage of windthrow differed significantly among all species (α = 0.05) and between height or diameter classes of a given species (α = 0.05) when compared by a chi-square contingency test.

Variables Related to Shading

ACD of the 28 shade-providing strips ranged from 15 to 87 percent (average 51). In the 12 strips bounded on the south by uncut forest, it ranged from 26 to 83 percent (average 62). When ACD was regressed against WIDTH, ORIGBA, SLPCC, and SLPCRK, a statistically significant relationship was obtained:

$$\begin{aligned} \text{ACD} &= 27.5 + 0.0582\ \text{ORIGBA} - 0.861\ \text{SLPCC} \\ &+ 0.817\ \text{SLPCRK}. \quad (2) \\ R^2 &= 0.56 \end{aligned}$$

The relation of ACD to buffer-strip width was curvilinear (*fig. 2*):

$$\begin{aligned} \text{ACD} &= 100 - 109.3(e^{-0.01382\ \text{WIDTH}}). \quad (3) \\ R^2 &= 0.51 \end{aligned}$$

Buffer Strip Design

If management objectives do not indicate other stream-protection methods (see Dykstra and Froehlich 1976), properly designed buffer strips can be stable and can provide adequate shade for stream ecosystems. Stability and shading effectiveness of a proposed strip can be evaluated after data for the variables shown in *table 2* are obtained and entered into Equations 1, 2, and 3.

First, site reconnaissance of local topography, vegetation, and stability is necessary to obtain basic information for buffer-strip location. Streambank slope (SLPCRK) and ad-

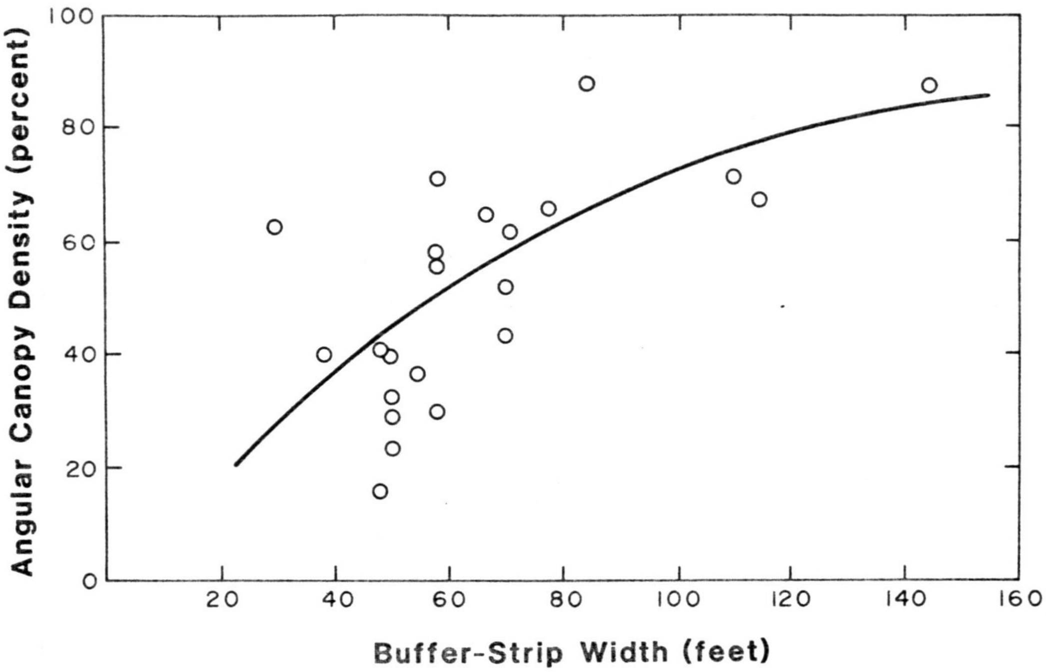

Figure 2. Regression functions relating angular canopy density (ACD) to buffer-strip width.

jacent clearcut slope (SLPCC) can then be measured. Old windfalls and pit and mound topography can be assessed for the direction of damaging wind and potential for future windthrow. Understory species should also be identified, and the moisture status of the site should be evaluated.

Second, general stand conditions and overstory species composition can be used to assess windthrow susceptibility. Indicators of potential natural instability should be noted, including streambank cutting, large debris jams, swampy areas, and landslide scars. Jackstrawed trees may indicate poor natural stability; trees with butt or stem rot may be especially susceptible to windsnap upon exposure (Ruth and Yoder 1953); and trees in a dense stand that shelter one another from damaging winds may not be as windfirm as trees growing in an open stand (Gratowski 1956, Mergen 1954). Short, stocky trees have a form point that gives them good stability (Curtis 1943). Also, windswept trees have an inherent stability (Smith 1962).

Third, the proposed buffer strip should be plotted on a topographic map with the proposed harvest unit. Measurements that can be obtained from a map are DISTWIND, DISTRIDG, ORIENT, and ELEV.

Last, timber volume and basal area (ORIGBA) of the riparian zone can be estimated from the cruise conducted for the sale area. Multiplying the original timber volume by moisture class gives WETVOL.

Entering the appropriate data into Equation 1 gives an estimate of the stability of a proposed buffer strip. Distance to the cutting line in the direction of damaging winds is the most readily manipulated variable in the equation. Shortening the distance may improve survival. It may be necessary to substitute a range of distance values into the equation to arrive at the best compromise between harvesting efficiency and buffer strip survival.

Equation 2 provides an estimate of shading based on two existing topographic variables and one timber variable. If results from Equation 2 indicate that a buffer strip would be beneficial, appropriate data can be entered in Equation 3 to determine the optimum strip width.

Ultimately, the land manager must rely on professional judgment to evaluate the suitability of buffer strips for given management objectives and alternatives, but the equations can aid that judgment. Those given here best apply to conditions existing in the area of this study. Extrapolation to other areas may diminish their applicability, and require increased judgment to provide reasonable predictions. ■

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