A Coarse Wood Dynamics Model for the Western Cascades[1]

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Abstract

The Coarse Wood Dynamics Model (CWDM) analyzes the dynamics (fall, fragmentation, and decomposition) of Douglas-fir *(Pseudotsuga menziesii)* and western hemlock *(Tsuga heterophylla)* snags and down logs in forested ecosystems of the western Cascades of Oregon and Washington. The model predicts snag fall, height loss and decay, and log decay at 5-year intervals for a period of 300 years. Snags either fall whole or in parts, creating down logs. Snags also decay from a hard to soft condition. Logs decay more slowly than snags, from sound to decayed conditions, and eventually disappear into the forest floor as duff. Snag fall and height loss rates were derived from Forest Inventory and Analysis (FIA) remeasurement data on private lands in western Washington. Decay rates were obtained from various studies conducted in the western Cascades of Oregon and Washington. The model can track remnant snags and logs (i.e., those existing on site at the beginning of the assessment time) and new snags and logs created from green trees.

Introduction

Managers of forested lands in the Pacific Northwest are required to manage for snags and logs, or coarse woody debris (CWD), in timber harvest units. Coarse woody debris is a highly dynamic ecosystem component, as snags fall over time and both snags and logs decay. Therefore, managing for these habitat components through time requires knowledge of the dynamics of CWD. Snag dynamics models that predict the general rate of fall and decay of snags have been available for several years (Marcot 1992, McComb and Ohmann 1996). These models estimate the number of green trees that need to be retained in harvest units to replace existing snags that will fall during a rotation, and to estimate when to convert green trees to snags. Mortality estimates from growth and yield models can be input into these models to track snag recruitment in forest stands. The Snag Recruitment Simulator (SRS) (Marcot 1992) has been widely used in Land and Resource Management Plans by the USDA Forest Service in the Pacific Northwest.

The main drawback of these models is that they do not assess the dynamics of logs. In order to manage logs through time, it is important to know how they decompose over time. Wright (1998) developed a model that predicted the dynamics of CWD mass through time, although snag and log biomass were aggregated. The

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objective of our Coarse Wood Dynamics Model (CWDM) is to predict the dynamics of snags and logs as separate entities through time. The CWDM provides output on amounts of CWD, distinguishing between snags and logs of different size and decay classes, every 5 years for a period of up to 300 years.

Model Overview

The CWDM analyzes the dynamics of CWD in forested ecosystems of the western Cascades in Oregon and Washington. The CWDM models Douglas-fir *(Pseudotsuga menziesii)* and western hemlock *(Tsuga heterophylla)* snags and logs. The model predicts snag fall, height loss and decay, and log decay at 5-year intervals for a period of 300 years. Snags either fall whole or partially break off, creating down logs. Snags also decay from hard to soft. Logs decay from sound to decayed conditions, and eventually disappear into the forest floor as duff. The model simulates the decomposition of remnant snags and logs (those existing on site at the beginning of the assessment time) and new snags and logs created from green trees or from mortality. A growth and yield model can be used to determine number and sizes of snags created by suppression mortality. These snags can then be input into the model at the appropriate time during the rotation.

The CWDM follows individual CWD pieces or groups of pieces (same species, size and decay class) through time. The model varies snag fall and height loss rates by species, diameter at breast height (dbh), and decay class. Western hemlock snags fall faster than Douglas-fir snags, and smaller more decayed snags fall faster than larger, sounder snags. Decay is basically the reduction in density of a piece of CWD. Decay rates are different for snags and logs since snags decay faster than logs. The model varies decay of snags and logs by species and size. Western hemlock decays faster than Douglas-fir *(fig. 1).* Smaller snags and logs decay faster than larger ones.

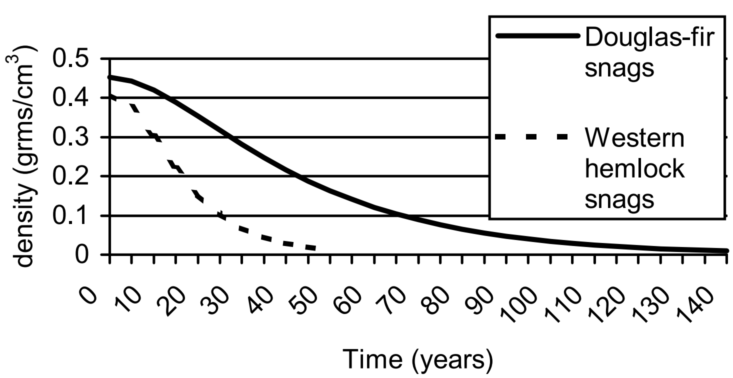

Figure 1—CWDM decay of Douglas-fir and western hemlock snags ranging from 38.1 to 63.5 cm dbh.

Although the current version of the CWDM uses data from the western Cascades of Oregon and Washington, the model could easily be modified to include data from other geographic locations. The same approach taken in the model could also be used to incorporate other species of snags and logs as data become available.

The CWDM is compiled to run in DOS. A Windows version will be released soon.[4] The program and documentation are available from the lead author.

Model Input

CWDM requires input data in the form of two space-delimited ASCII files, one each for snags and logs. The following data are required in the snag input file: year snag created (0 for existing snags), snag species, decay class, dbh (in), height (ft), snags/acre or ha, and site class. The log input includes year log created (0 for existing logs) log species, decay class, large end diameter (in), length (ft), and logs/acre or ha.

A 3-class decay system is used for both snags and logs. Snags are divided into green, hard, or soft snags. Logs are divided into green, sound, or decayed logs. Green snags and logs are those created at the current time either through natural mortality or artificial creation. Hard snags include classes 1-3 and soft snags classes 4 and 5 of the 5-class system developed by Cline and others (1980). Sound logs include classes 1 and 2, while decayed logs include classes 3-5 of the 5-class system developed by Maser and others (1979) for logs.

Model Outputs

The CWDM creates five space-delimited ASCII output files: snagout, logout, snlogout, sumsnags.txt and sumlogs.txt. The first three files are intermediate files that track individual snags or logs through time. The last two are summary files that most users will want to view. The files are sums of snags and logs by time, species, decay class, and dbh or diameter class. Dbh classes for snags are <38.1 cm, 38.1-63.5 cm, and ≥63.5 cm. Diameter classes for logs are <30.5 cm, 30.5-50.8 cm, and ≥50.8 cm. If different dbh or diameter breaks are desired, the snagout and logout files can be imported into a database and for querying.

The fields in sumsnags.txt are time, species, decay class, dbh class, and snags/acre or ha. The fields in sumlogs.txt are time, species, decay class, diameter class, linear feet/acre or ha, and percent cover.

Example Outputs

Figures 2-4 are examples of results from the model. The current version of the CWDM does not produce graphs. Graphic representations can be developed by importing the ASCII files into a spreadsheet or database program with graphing capabilities.

Figure 2 is the result of leaving a mix of species, size, and decay classes of snags on site at time 0. The loss of hard snags is a result of some snags falling and some snags becoming soft. The first increase in the soft snags is when western

[4] Mention of trade names or products is for information only and does not imply endorsement by the U.S. Department of Agriculture.

hemlock snags change from a hard to soft condition. The second increase is from hard Douglas-fir snags becoming soft. The decrease in total numbers of snags is from snag fall.

Figure 3 illustrates the results of recruitment of snags during a time period. In this example a mixture of species, sizes, and decay classes of snags is left at time 0. A few snags are artificially created at years 25 and 50 to replace snags that have fallen. Suppression mortality creates snags ≥ 38.1 cm beginning at year 75. Input from suppression mortality continues until year 95 in this example. Realistically, suppression mortality would continue beyond 95 years, but this is the limit of some growth and yield models.

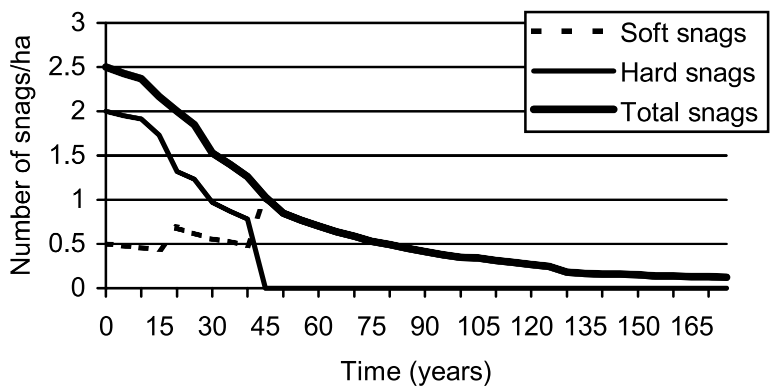

Figure 2—CWDM decrease in the number of snags through time. Loss of total and soft snags is a result of snag fall. Loss of hard snags is a result of decay to the soft decay class and fall. Input at time 0 includes a mixture of hard and soft Douglas-fir and western hemlock snags for a total of 2.5 snags/ha.

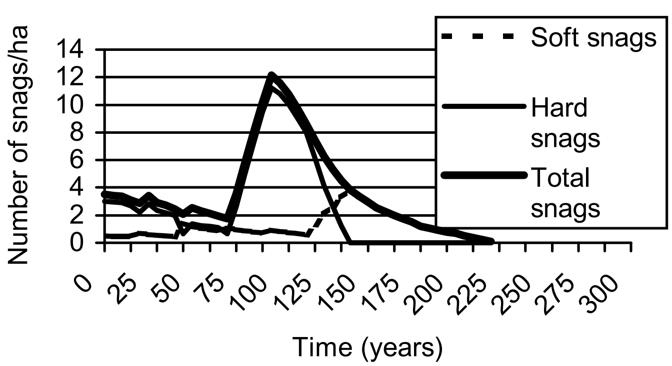

Figure 3—CWDM dynamics of snags through time with recruitment of snags during the rotation. Input at time 0 includes a mixture of hard and soft Douglas-fir and western hemlock snags. Recruitment of snags includes snags artificially created from Douglas-fir trees at years 25 and 50, and from suppression mortality of Douglas-fir trees at years 75, 80, 85, 90, and 95.

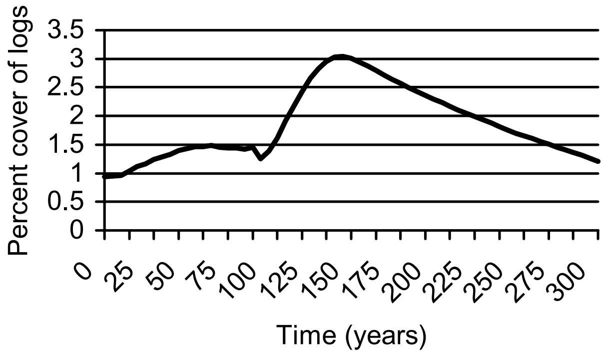

Figure 4—CWDM percent cover of logs through time with recruitment of logs from snags. Input of logs at time 0 is < 1 percent cover. Recruitment of logs through time is all from snags falling as per *figure 3*. Initial input of logs at time 0 includes a mixture of green and sound Douglas-fir and western hemlock logs.

Figure 4 illustrates an example of leaving some sound and green logs on site at time 0 and then incorporates the snags displayed in *figure 3* as they fall partially or whole and become logs. Percent cover of logs is also reduced as they decay.

Assumptions

Given the available data, a number of assumptions were required to develop the model. Foremost is that values for snag and log dynamics reported in the literature are "average." CWD decay is highly variable and highly dependent on site conditions, weather, geographic location, etc. Since the model takes each snag or log and treats it as an average piece on an average site, the model outputs should be considered as general guidelines and should be applied over larger areas or landscapes.

Because data for western hemlock are very limited, we used more substantial data for Douglas-fir to develop size-specific values used for western hemlock decay and fall rates. It is clear from data that are available that western hemlock CWD falls and decays much faster than Douglas-fir CWD.

The model assumes snags fall at a constant rate over time, varying only by dbh and decay class. In reality snags probably are created and fall in "pulses" over time. The pulses are difficult to predict and thus are not incorporated in the model. This omission should have little effect on the ability of the CWDM to predict the general dynamics of CWD levels throughout a rotation or planning cycle.

It is assumed that there is a lagtime once a green tree becomes a snag before it begins to decay and fall. Lagtimes were applied to snags created from green trees.

Several assumptions were made regarding the process by which snags break and fall. It was assumed that snags often break and fall in two to three pieces, although some snags also fall whole. At any one time, some snags will lose a portion of their original height. Height loss was averaged for snags. Based on Pacific Northwest Research Station (PNW) Forest Inventory and Analysis (FIA) program data, it was assumed that on average one-third of a snag falls when it loses height. Taper equations were used to determine two-thirds height diameter of snags to determine large end diameter of the log. To calculate the number of log pieces, we assumed that 27 percent of standing snags lost a portion of their height over a 5-year period (based on FIA data). Class 5 snags that fall are not counted as logs. They were assumed to disintegrate and contribute to the duff layer.

For snags it is assumed that volume (m^3/ha) is constant except for the portion of snag height that breaks off during the time period. As snags move toward decay class 5 this assumption is probably violated, as dbh is also reduced by fragmentation of the snag. As a result, calculations for very soft snags probably underestimate density.

For Douglas-fir logs it was assumed that volume is constant until the log reaches the class 4 decay stage (Graham 1982). Volume of class 4 and 5 logs is "decayed" using fragmentation rates. Fragmentation rates were obtained from Graham (1982). Diameter and length of logs were also reduced for decay class 4 and 5 logs based on Maser and Trappe (1984). Western hemlock logs do not fragment like Douglas-fir because bark remains intact, forming a protective shell around the log (Graham 1982).

It was assumed that, on average, existing snags and logs are halfway through either the hard or soft decay class for snags or sound or decayed class for logs. Densities were assigned based on midpoint densities of either the hard or soft decay class.

Decay rates were applied to biomass in equations in the CWDM. Decay rates are a combination of mineralization and fragmentation of boles. Both types of decay reduce biomass: mineralization reduces density, and fragmentation reduces volume. In the model the two types of decay were usually combined. In the case of decayed logs, fragmentation rates were applied to the log volume.

The Smalian formula (Wegner 1984) was used to calculate volume. This volume is then multiplied by decay class specific density to get biomass. Because the Smalian formula tends to overestimate volume by about 10 percent (Wegner 1984), biomass is overestimated. This is not a problem with the decay equations in the model because decay is relative; thus, differences in biomass do not influence rate of decay. However, biomass and volume results should not be used as the absolutes for CWD in a stand.

Data Sources

Information on decay rates *(tables 1, 2)* was gleaned from the literature. Decay rates for Douglas-fir snags are from Graham (1982). Decay rates for Douglas-fir logs are from 3 sources: decay rates for logs >38.1 cm diameter are from Graham (1982); decay rates for logs 15.2-38.1 cm diameter are from Means (in Harmon and others 1986); and decay rates for logs < 15.2 cm diameter are from Erickson and others (1985).

Less data are available for decay of western hemlock. An overall decay rate for logs and snags is given by Graham (1982), but size-specific decay rates are not available. Decay rates for three size classes are extrapolated based on comparative fall rates of snags in the different size classes. It was assumed that fall rates indicated relative fragmentation rates. The logic was checked by trying the same extrapolation with Douglas-fir snags and comparing to reported decay rates. The result was close;

extrapolated decay rates were within 0.003 (or 85 percent). Decay rates for largest logs are extrapolated based on Douglas-fir decay rates. Decay rates for logs <15.2 cm diameter are from Erickson and others (1985).

Table 1—*Snag decay rates used in the CWDM.*

Species[1]	Dbh class (cm)	Decay rate (k)	Decay lagtime[2] (years)	Lagtime decay constant[2]
DF	≥ 63.5	0.017	20	0.06
DF	38.1 – 63.5	0.033	15	0.14
DF	< 38.1	0.053	10	0.25
WH	≥ 63.5	0.060	15	0.15
WH	38.1 – 63.5	0.088	10	0.25
WH	< 38.1	0.100	5	0.30

[1] DF = Douglas-fir; WH = western hemlock
[2] Decay lagtime and constant applied to newly created snags only.

Table 2—*Log decay and fragmentation rates used in the CWDM.*

Species[1]	Diameter class (cm)	Decay rate (k)	Fragmentation rate[2] (kf)	Diameter reduction rate[2] (rd)	Length reduction rate[2] (rl)
DF	≥ 38.1	0.012	0.008	0.0031	0.0026
DF	15.2 – 38.1	0.015	0.010	0.0037	0.0030
DF	<15.2	0.026			
WH	≥ 38.1	0.019			
WH	15.2 – 38.1	0.023			
WH	<15.2	0.030			

[1] DF = Douglas-fir; WH = western hemlock
[2] Fragmentation, diameter reduction and length reduction rates apply to class 4 and 5 Douglas-fir logs only.

Snag fall and height loss rates *(table 3)* are based on remeasurement data from snags on private lands. The data were collected through the PNW FIA program.[5] The snags were measured in the late 1970s and again in the late 1980s. Presence or absence of snags were noted, and changes in height and decay class were recorded. Using FIA data, snags that disappeared during the 10-year remeasurement period are assumed to have fallen whole. The 10-year fall and height loss rates were converted to 1-year rates. Fall and height loss rates were averaged for size class (<38.1, 38.1-63.5, ≥63.5 cm dbh) and decay class (hard vs. soft) *(table 3)*. Size and decay classes were lumped if there was no significant difference (alpha=0.20) in rates of fall or height loss. A large alpha value was used because the effect of a type 1 error was considered less risky to the outcome of the model than a type 2 error. Sample sizes are small and data are variable, but the trends in the data supported what is known from other data about relative fall rates of snags.

[5] Unpublished data on file, Pacific Northwest Research Station, Janet Ohmann, Portland, Oregon.

Table 3— *Snag fall rates and height loss proportions used in CWDM.*

Species[1]	Diameter class (cm)	Decay class[2]	Fall rate (p)	Height loss proportion (p)	Fall lagtime[3]
DF	≥ 63.5	Hard	0.008	0.019	15
DF	≥ 63.5	Intermediate	0.008	0.019	
DF	≥ 63.5	Soft	0.008	0.019	
DF	38.1 – 63.5	Hard	0.013	0.033	10
DF	38.1 – 63.5	Intermediate	0.022	0.038	
DF	38.1 – 63.5	Soft	0.027	0.041	
DF	< 38.1	Hard	0.021	0.042	0
DF	< 38.1	Intermediate	0.043	0.056	
DF	< 38.1	Soft	0.054	0.063	
WH	≥ 63.5	Hard	0.01	0.024	5
WH	≥ 63.5	Intermediate	0.017	0.029	
WH	≥ 63.5	Soft	0.021	0.031	
WH	38.1 – 63.5	Hard	0.02	0.035	0
WH	38.1 – 63.5	Intermediate	0.03	0.044	
WH	38.1 – 63.5	Soft	0.035	0.048	
WH	< 38.1	Hard	0.03	0.035	0
WH	< 38.1	Intermediate	0.039	0.044	
WH	< 38.1	Soft	0.044	0.048	

[1] DF = Douglas-fir; WH = western hemlock
[2] Decay classes reflect groups of the 5-stage system developed by Cline and others (1980). Hard = 1 and 2 =; Intermediate 3; Soft = 4 and 5.
3 Fall lagtimes applied to newly created snags only.

The sharp change in fall and height loss rates between hard and soft snags caused calculation problems for the model because snags gained height as they went from hard to soft. As a result, intermediate fall and height loss rates are applied to class 3 snags *(table 3).* Since there are 3 classes in the broad category of "hard," two-thirds of the difference between hard and soft fall and height loss rates is added to the "hard" class rates to determine intermediate rates for class 3 snags. Using intermediate rates smoothes the decay curves but does not change the long-term decay and fall of snags.

Lagtimes for beginning of snag decay and fall *(tables 1, 3)* are from Cline and others (1980) and Harmon and others (1986). Data on lagtimes for western hemlock snags are not dbh specific. Lagtimes for the 3 dbh classes are based on extrapolating the relationship of increase in lagtime with increase in dbh for Douglas-fir snags and applying the extrapolation to western hemlock snags.

Taper equations from Walters and Hann (1986) are used to calculate top and mid-height diameter of snags. Mid-height diameter is needed to determine large end diameter of logs created as snags break. Both diameters are used in volume calculations. The taper calculations require knowing the height and crown ratio of the tree before it became a snag. Forest Service Continuous Vegetation Survey (CVS) data from the Mt. Hood and Gifford Pinchot National Forests were used to determine average height and crown ratio of trees of a given dbh on low, moderate, and high sites.[6] Only data on live trees without broken or deformed tops were used for the

[6] Unpublished data on file, Pacific Northwest Region, Portland, Oregon.

estimates of height and crown ratio. Average height was calculated for 12.7 cm-dbh classes up to 101.6 cm dbh and by 25.4 cm-dbh classes for dbh greater than 101.6 cm. Height and crown ratio were determined for dbh classes of <38.1 cm, 38.1-63.5 cm and ≥63.5 cm. Only significant differences (alpha =0.05) were used; otherwise, height and crown ratio were averaged over two or more dbh classes. Plant associations (Brockway and others 1983, Halverson and others 1985, Hemstrom and others 1982, Topik and others 1986) were used to determine if data were from high, moderate, or low sites. High and moderate sites were in plant association where average growth was ≥ 6 m^3/ha/year. Growth on low sites was < 6 m^3/ha/year. Because there was no significant difference between height crown ratio on high and moderate sites, data for those sites were lumped.

The Walters and Hann (1986) equations used for calculating taper for snags can not be used directly on logs, because large end diameter does not necessarily relate to dbh of a tree that is needed to calculate taper. Data Jane Kertis and Mark Huff [7] on log length and small end and large end diameters, were used to determine small end diameter of logs given large end diameter and length. The data are from the Willamette National Forest in the western Oregon Cascades. Small end/large end ratios were calculated for each log. Simple linear regression was used to determine the relationship between log length and the small end/large end ratio. For Douglas-fir logs, sound and decayed logs were assessed separately. For western hemlock logs, sound and decayed logs were combined. Class 5 logs were not used in the equations. The regressions were highly significant with the following *P*-values: Douglas-fir = 9.93 E-33; western hemlock = 5.33 E-10.

Densities of snags and logs (g/cm^3) *(tables 4-7)* are needed to convert volume to biomass for the decay equations and to determine decay class of snags and down logs. Densities for both Douglas-fir and western hemlock class 1-5 snags and logs are from Spies and others (1988). Densities for green snags and logs are from Harmon (1992).

Snags and logs are removed from the model when they reach a maximum age *(tables 4-7)*. Maximum age of Douglas-fir snags is from Cline and others (1980). Maximum ages for all logs and western hemlock snags are from Graham (1982) and half-life data are from Harmon and others (1986).

Table 4—*Density and ages for decay classes of Douglas-fir snags used in the CWDM. Values are for snags as they first enter a decay class. Ages are based on output from the model.*

		Dbh class (cm)		
Decay class	**Density (gm/cm^3)**	**≥ 63.5**	**38.1 – 63.5**	**< 38.1**
			Snag ages (yrs)	
1	0.452	0	0	0
2	0.380	15	15	15
3	0.284	35	30	25
4	0.197	60	45	30
5	0.140	80	60	40
Maximum age		250	130	75

[7] Unpublished data on file, Willamette National Forest, Jane Kertis and Mark Huff, Eugene, Oregon.

Table 5—*Density and ages for decay classes of western hemlock snags used in the CWDM. Values are for snags as they first enter a decay class. Ages are based on output from the model.*

		Dbh class (cm)		
Decay class	**Density (gm/cm^3)**	**≥ 63.5**	**38.1 – 63.5**	**< 38.1**
		Snag ages (yrs)		
1	0.408	0	0	0
2	0.348	10	10	5
3	0.263	20	15	10
4	0.215	25	20	10
5	0.138	30	25	15
Maximum age		85	50	35

Table 6—*Density and ages for decay classes of Douglas-fir logs used in the CWDM. Values are for logs as they first enter a decay class. Ages are based on output from the model.*

		Diameter class (cm)		
Decay class	**Density (gm/cm^3)**	**≥ 38.1**	**15.2 – 38.1**	**< 15.2**
		Log ages (yrs)		
1	0.452	0	0	0
2	0.380	15	15	10
3	0.284	40	35	20
4	0.197	70	60	35
5	0.140	155	115	45
Maximum age		315	245	70

Table 7—*Density and ages for decay classes of western hemlock logs used in the CWDM. Values are for logs as they first enter a decay class. Ages are based on output from the model.*

		Diameter class (cm)		
Decay class	**Density (gm/cm^3)**	**≥ 38.1**	**15.2 – 38.1**	**< 15.2**
		Log ages (yrs)		
1	0.408	0	0	0
2	0.348	10	10	10
3	0.263	25	20	15
4	0.215	35	30	25
5	0.138	60	50	40
Maximum age		95	75	60

Calculations

Equations

The following are the equations used to calculate parameters in the CWDM:

Parameter	**Equation**
Volume	
snags[1]	volume = ((Ab+At)/2)*L
logs (1-3)[1]	volume = ((Ab+At)/2)*L
logs (4-5)[2]	current volume = initial volume*(EXP(-kf(t-tIV)))
Decay	
green snags[3]	current biomass = initial biomass*(1-(1(EXP(-kt))$^{(lt*lc)}$
hard/soft snags[4]	current biomass = initial biomass*(EXP(-kt))
logs[4]	current biomass = initial biomass*(EXP(-kt))
Snag fall[5]	current snag/ha = original snag/ha*(EXP(-pt))
Snag height loss[6]	current height = original height*(1-p)^{t}
Log diameter[7]	current diameter = initial diameter*(EXP(-rd(t-tIV)))
Log length[8]	current length = initial length*(EXP(-rl(t-tIV)))
Log taper[9]	small end diam. = large end diam.*(Yintercept+(slope*L))
Log pct. cover[10]	Pct. cover = (((le diam*L)/2)+((se diam*L)/2))/100

[1] Smalian equation from Wegner (1984); Ab=area of base or large end; At=area of top or small end; L=snag height or log length.
[2] kf=fragmentation rate (see *table 2*); t=time elapsed; tIV=time at which logs becomes a class 4.
[3] Green snags are those created at the current time; k=decay rate (see *table 1*); t=time elapsed; lt=lagtime; lc=lagtime constant; see table 1 for lagtime and lagtime constant.
[4] Snags that are hard or soft at the beginning of the planning cycle; k=decay rate (see *tables 1* and *2*); t=time elapsed.
[5] p=proportion of snags falling per year (see *table 3*); t=time elapsed; applied after lagtime has elapsed.
[6] p=proportion of height lost per year (see *table 3*); t=time elapsed; applied after lagtime has elapsed.
[7] rd=diameter reduction rate (see *table 2*); t=time elapsed; tIV=time at which logs becomes a class 4.
[8] rl=length reduction rate (see *table 2*); t=time elapsed; tIV=time at which logs becomes a class 4.
[9] L=length; for Douglas-fir Yintercept=0.884, slope=-0.0044; for western hemlock Yintercept=0.902, slope=-0.0055; small and large end diameter and length are used in calculations for volume and percent cover.
[10] le diam=large end diameter (in); se diam=small end diameter (in); L=length (ft)

Discussion of Calculations

A lagtime decay equation is used for snags created from green trees to account for a lag between death of a tree and the beginning of decay. The equation is from Harmon and others (1986). Lagtime constants were determined by trial and error. Constants that resulted in a decay curve that approximated those in Cline and others (1980) were used.

When modeling decay of snags created from green trees, the results indicate that biomass lost during the lagtime was all due to mineralization. In reality, some snags probably break or fall, but very few due to lagtime for falling. Lagtime equations similar to the one used for decay did not work for fall and height loss calculations. The curves became too steep and didn't match fall rates (Cline and others 1980). Thus, absolute lagtimes are used. It is assumed that no snags fall during the lagtime.

Rates for reduction of log diameter and length are from Maser and Trappe (1984). Length of Douglas-fir logs decreases 55 percent between class 1 and class 5, and diameter is reduced by 68 percent, mostly due to bark loss. Rates (rd and rl) are calculated by taking the number of years to get halfway between the beginning of the class 5 condition and the maximum life of the log and then dividing the percent reduction by that number of years.

The density at which a snag changes from hard to soft was determined by bracketing the average densities for the decay classes 3 and 4 by the standard deviation of the density estimate. The density at which the upper bracket of class 4 and lower bracket of class 3 meet is used as the density that triggers classifying the snag as hard or soft *(tables 4, 5)*. Each snag was tracked through time, and as decay class changed the decay-specific fall rates were applied. The density at which logs go from sound to decayed was calculated in a manner similar to that for snag calculations except that class 2 and 3 densities were used *(tables 6, 7)*.

Densities for existing snags are assigned based on midpoint densities of either the hard or soft decay class. The midpoint density of hard snags was calculated by averaging densities for class 3 and green tree densities. The midpoint density for soft snags was calculated by averaging densities for class 4 and 5 snags. The midpoint density for sound logs was calculated by averaging densities for class 2 and green tree densities. The midpoint density for decayed logs was calculated by averaging densities for class 3 and class 5 logs.

Model Validation

Data from Cline and others (1980) were used to validate the fit of the model for Douglas-fir snags against the decay rates used in the model (Graham 1982). Age at which a snag went from hard to soft for different dbh classes and the maximum life of snags from the CWDM was validated against data in Cline and others (1980). Because dbh breaks did not match exactly between the two studies, generalized extrapolations were made. Data were not available to validate western hemlock snag decay and fall.

For logs, decay rates and equations in the model were tested against age range for each decay class in Graham (1982). This is not a true validation because decay rates and ages came from the same data set—it just validates that the equations and values used were producing the expected results. Half-lives from two additional datasets (reported in table 3 of Harmon and others 1986) were also used to help validate decay rates. Data from Sollins and others (1987) were used to check the log decay rate against ages of logs in decay classes 1 to 4.

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