Effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes states, U.S.A.

Matthew D. Duvall and David F. Grigal

Abstract: Coarse woody debris (CWD) chronosequences were developed for managed and unmanaged red pine (*Pinus resinosa* Ait.) stands across the Great Lakes states. Throughout stand development, there is less CWD in managed than in unmanaged forests, and effects of management are strongest in young forests (0–30 years old). At stand initiation, CWD is 80% lower in managed than unmanaged forests, 20 200 versus 113 200 kg·ha^{-1}, while at 90 years, CWD is 35% lower, 6600 versus 10 400 kg·ha^{-1}. Timber management especially affects snags. In young managed forests, snag biomass is less than 1% of that in unmanaged forests, 150 versus 58 200 kg·ha^{-1}, while log biomass is 80% lower, 5000 versus 22 800 kg·ha^{-1}. This trend continues in mature forests (91–150 years old), where snag biomass is 75% lower in managed than in unmanaged forests, 1700 versus 6400 kg·ha^{-1}. Management has relatively little impact on total log biomass of mature forests but increases the biomass of fresh logs nearly 10-fold, to 1400 versus 150 kg·ha^{-1}. CWD in managed forests is highly variable, primarily related to thinning schedules in individual stands.

Résumé : Des chronoséquences des débris ligneux grossiers ont été développées pour des peuplements aménagés et non aménagés de pin rouge (*Pinus resinosa* Ait.) dans les États des Grands Lacs. Au cours du développement du peuplement, il y a moins de débris ligneux grossiers dans les forêts aménagées que dans les forêts non aménagées et les effets de l'aménagement sont les plus prononcés dans les jeunes forêts (0–30 ans). Au moment de l'établissement du peuplement, il y a 80% moins de débris ligneux grossiers dans les forêts aménagées que dans les forêts non aménagées, 20 200 versus 113 200 kg·ha^{-1}, tandis qu'à 90 ans il y en a 35% de moins, 6600 versus 10 400 kg·ha^{-1}. L'aménagement forestier affecte particulièrement les chicots. Dans les jeunes forêts aménagées, la biomasse des chicots représente moins de 1% de celle qu'on observe dans les forêts non aménagées, 150 versus 58 200 kg·ha^{-1}, tandis que la biomasse des billes au sol est 80% plus faible, avec 5000 versus 22 800 kg·ha^{-1}. Cette tendance se maintient dans les forêts matures (91–150 ans) où la biomasse des chicots est 75% plus faible dans les forêts aménagées que dans les forêts non aménagées, 1700 versus 6400 kg·ha^{-1}. L'aménagement a relativement peu d'impact sur la biomasse totale des billes au sol dans les forêts matures mais augmente par un facteur de près de 10 la biomasse des billes au sol dont l'origine est récente, à 1400 versus 150 kg·ha^{-1}. Dans les forêts aménagées, la quantité de débris ligneux grossiers est très variable et est principalement reliée aux programmes d'éclaircie des peuplements individuels.

[Traduit par la Rédaction]

Introduction

Coarse woody debris (CWD), both standing dead trees and pieces of dead wood that have fallen to the forest floor, is important in a wide variety of forest ecosystem processes, including the accumulation of soil organic matter (e.g., McFee and Stone 1966), nutrient cycling (e.g., Jurgensen et al. 1992), soil hydrology (e.g., Harvey et al. 1981), soil biology (e.g., Maser and Trappe 1984), forest fire behavior (e.g., Agee and Huff 1987), insect populations (e.g., Maser and Trappe 1984), tree pathogens (e.g., Childs 1939), erosion (e.g., Robison and Beschta 1990), wildlife habitat (e.g., Cline et al. 1980), and micro-sites for regeneration (e.g., Harmon and Franklin 1989). CWD from forest ecosystems can also affect neighboring riparian and aquatic environments (e.g., Robison and Beschta 1990). Because timber management affects the distribution of CWD (e.g., Spies et al. 1988), it thereby affects related ecosystem processes.

The distribution of CWD is determined by the balance between inputs and outputs of dead wood, which change during stand development. At stand initiation, all CWD is relict from the previous stand and may be very abundant. During stand establishment, intraspecific competition and mortality are negligible and changes in CWD are primarily due to decomposition. Accumulation of new CWD begins during stem exclusion and continues into understory reinitiation. In the stem-exclusion phase, mortality is relatively high but the trees are small so inputs of CWD are similarly small. During understory reinitiation, the rate of overstory mortality slows but individual dead trees can be large. As the stand moves towards an old-aged condition, CWD approaches a "steady state," reflecting a hypothetical balance between mortality and decomposition. Red pine (*Pinus resinosa* Ait.) forests in

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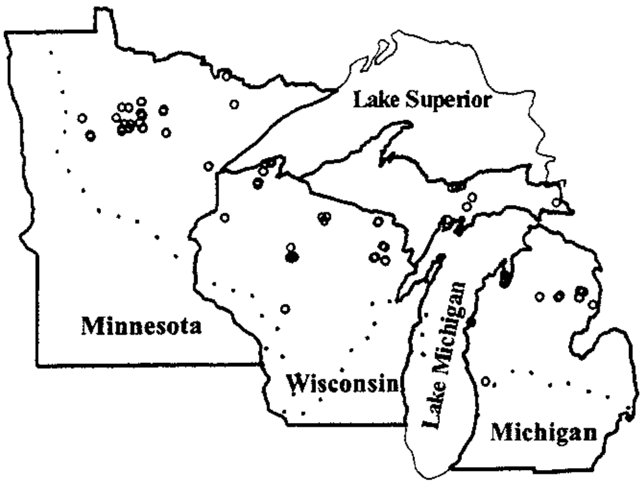
Fig. 1. The locations of inventory sites for CWD (o) across the western Great Lakes states in relationship with the southern border (- - -) of the historical (botanical) range of red pine (Burns and Honkala 1990). More than one stand was inventoried at several sites. A total of 99 stands were inventoried.



the western Great Lakes states exhibit these four stages of development, roughly between 0–30, 31–90, 91–150, and greater than 150 years of age (based on data interpreted from Buckman 1962). A generalized chronosequence of CWD can therefore be developed for regional forests (e.g., Spies et al. 1988).

Individual stands vary from this generalized chronosequence because of their unique history. Stand-level fluctuations are caused by the variability associated with disturbances, changes in local environmental factors that influence mortality and decomposition, and the silvical characteristics of specific stand-level species mixtures. For example, a catastrophic stand-replacing fire produces a large input of CWD, and while harvesting may remove much of the potential CWD as logs, it also produces CWD as slash. Similarly, intermediate disturbances such as small patch blowdowns, bark beetle attacks, and thinning may produce important inputs of CWD in individual stands. Thinning may also reduce accumulations of CWD by controlling competition and mortality and also by removing logs. Although harvesting produces inputs of CWD as slash, most material is small and occurs on the forest floor and not as standing snags. Outputs of CWD by decomposition also vary among stands because of differences in environment and stand development (e.g., size of material). Decomposition varies by diameter (e.g., Erickson et al. 1985), decay state (e.g., Schowalter 1992), species (e.g., Erickson et al. 1985), by position; e.g., downed logs versus standing snags (e.g., Harmon et al. 1986), and by climate (e.g., Bunnell et al. 1977). CWD on exposed sites can also develop case hardening, inhibiting moisture absorption and limiting decay (Erickson et al. 1985). A general chronosequence can therefore represent total amounts of CWD, but may neglect subtle but ecologically important structural considerations, including the relative abundance of snags and logs, their size distribution, and the proportion of CWD in various stages of decay.

The objective of this research was to compare the effects of timber management on total amounts and structural characteristics of CWD with similar measures in unmanaged forests throughout stand development. Red pine forests were studied because they are abundant and commercially valuable across the Great Lakes states.

Methods

An inventory of CWD was conducted in 99 managed and unmanaged red pine stands, ranging from 0 to more than 350 years old, and distributed throughout the historic (botanical) range of red pine across the western Great Lakes states of the U.S.A. (Fig. 1). Red pine was the dominant species in all stands, representing at least 50% of the overstory. The location, age, and history of each stand are presented in detail in Duvall (1997).

Unmanaged forest data set

There were 24 stands in the unmanaged data set, all of which originated following catastrophic fire in former red pine stands, the primary means of natural regeneration for these forests (Burns and Honkala 1990). Origination of red pine forests from other disturbance events (e.g., catastrophic windthrow) is unlikely. As a result of successful fire exclusion across the region from the 1920s to the early 1970s, there were no fire-origin stands between the ages of 24 and 79 years old, necessitating a modification of the analysis (Duvall 1997). Data for unmanaged red pine forests would ideally be based entirely on stands that had never been harvested, but that scenario is impossible in the western Great Lakes states. A few of these stands had experienced some timber removal during salvage harvests, but not within the past 30 years. These stands were included because they either are or were being considered for old growth reserves or natural history areas. The salvage harvests should reduce any differences between the unmanaged and managed data sets.

Managed forest data sets

The data set of 75 managed stands includes plantations less than 35 years old, regardless of whether they have been thinned, and plantations and natural stands that had been thinned within 30 years of our inventory. The stands have variable treatment histories, including those subject to whole-tree and shortwood harvests, single and multiple harvests, sites prepared with and without slash removal, and many combinations of these factors. Plantations older than 35 years that have never been thinned were not included in the data set because timber management typically begins at 30 years of age (Lundgren 1981).

The data were divided into three subsets reflecting the timing of the most recent commercial thinning harvest. All of these chronosequences shared the same 15 stands for the period of stand establishment (0–30 years), but the latter stages of stand development were divided by (1) 17 stands thinned within 5 years of inventory, (2) 24 stands thinned between 5 and 10 years before inventory, and (3) 19 stands thinned more than 10 years but less than 30 years before inventory. We based this division on the standard 10-year thinning cycle across the Great Lakes states, which is highly effective at capturing mortality (Lundgren 1981) and should therefore have strong ramifications on CWD. We excluded stands with atypical thinning regimes such as those that had been thinned 5 or more times prior to the most recent thinning. These exclusions should again reduce the differences between the unmanaged and managed data sets.

CWD inventory

Within each stand, volume of CWD was inventoried on six sample points evenly spaced along a set of parallel grid lines. Each sample point served as both the center of a variable-radius point plot for the inventory of snags (standing dead trees) and the end

Table 1. Descriptions of decay classes developed for this research.

Decay class	Description
Logs	
1	Bark on, wood sound and round
2	Bark partially off, wood partially decayed but round
3	Bark mostly off, wood decayed and exterior is friable, round to partially oval
4	No bark, wood very decayed and highly friable throughout, oval
Snags	
1	Recently dead, small twigs still present, bark intact, wood sound
2	Small twigs gone, most large branches still present, exterior wood partially unsound
3	Most large branches missing, bark falling off, wood unsound

Table 2. Mean densities for classes of CWD developed using factorial ANOVA described in Duvall (1997).

Density class				
Decay class	Species group*	Position	Mean density ($g \cdot cm^{-3}$)	SE ($g \cdot cm^{-3}$)
1	A	Log	0.37	0.013
1	A	Snag	0.38	0.015
1	HW	Log	0.49	0.009
1	HW	Snag	0.51	0.012
1	RP	Log	0.34	0.006
1	RP	Snag	0.35	0.009
1	SW	Log	0.35	0.009
1	SW	Snag	0.37	0.010
2	A	Log	0.30	0.025
2	A	Snag	0.27	0.028
2	HW	Log	0.34	0.015
2	HW	Snag	0.40	0.021
2	RP	Log	0.27	0.006
2	RP	Snag	0.30	0.011
2	SW	Log	0.30	0.014
2	SW	Snag	0.30	0.021
3	A	Log	0.16	0.054
3	A	Snag	0.22	0.054
3	HW	Log	0.15	0.031
3	HW	Snag	0.32	0.054
3	RP	Log	0.15	0.008
3	RP	Snag	0.23	0.011
3	SW	Log	0.18	0.019
3	SW	Snag	0.25	0.027
4	A	Log	0.11	0.054
4	HW	Log	0.10	0.031
4	RP	Log	0.11	0.009
4	SW	Log	0.15	0.054

*A is aspen, HW is hardwoods (broadleaf trees other than aspen), RP is red pine, and SW is softwoods (conifers other than red pine).

point of three line transects for the inventory of logs (fallen branches and boles) (Van Wagner 1968). A minimum diameter limit of 2.5 cm was used for both snags (at breast height) and logs (at the plane of intersection between a line transect and log). This provided an inventory of nearly all dead wood too large to be included in the forest floor horizon of a typical soil profile. Volume was computed for snags (Duvall 1997) and logs (Van Wagner 1968). For the analysis of structure, CWD was sorted into three size classes: small (diameters between 2.5 and 10 cm), medium (diameters between 10 and 25 cm), and large (>25 cm diameter).

Four decay classes were developed for logs and three for snags (Table 1).

The biomass of CWD in each stand was estimated by combining the volume inventory with estimates of CWD density based on 466 density samples with multiple subsamples of each (Duvall 1997). Densities were determined using field volume and ovendry weight after drying at 75°C for 5 days (120 h). Density was computed for 28 classes: three-way combinations of decay class, species group, and structural position (Table 2). Four species groups were used: red pine; softwoods (conifers other than red pine); aspen (***Populus*** sp.); and hardwoods (broadleaf trees other than aspen). Details of the factorial analysis of variance (ANOVA) used to develop these density classes are presented in Duvall (1997).

Developing chronosequences

Chronosequences of CWD volume and biomass were developed by nonlinear least-squares regression using age of inventoried stands as a surrogate for changes over time. During analysis, roughly 10% of each data set was withheld to test the ability of each chronosequence to describe the regional distribution of CWD. The nonlinear function was selected to describe the changes in CWD in a forest. Negative exponential decay of relict CWD was described by

$$[1] \qquad Y_t = Y_0 \, e^{-kt}$$

where t is time (stand age), Y_0 represents the initial amount of relict CWD at time zero (stand initiation), e is the base of natural logs, and k describes the rate at which the relict material decomposes (e.g., Olson 1963). Asymptotic accumulation of new CWD was described using a monomolecular function that begins at the origin:

$$[2] \qquad Y_t = A(1 - e^{-bt})$$

where b is a scale parameter that describes the rate of accumulation of new CWD and A is an asymptote that reflects a "steady state" of CWD as death and decomposition approach a balance (e.g., Hunt 1982). The summation of [1] and [2] therefore described the chronosequence function:

$$[3] \qquad Y_t = Y_0 \, e^{-kt} + A(1 - e^{-bt})$$

where Y_0, k, A, and b are regression parameters.

This function mathematically describes the two major processes determining the amount of CWD in forests, loss of relict CWD, and accumulation of new CWD. The shape of the chronosequence function is also well documented by previous research (e.g., Clark et al. 1998; Gore and Patterson 1986; Krankina et al. 1999; Maser et al. 1988; McCarthy and Bailey 1994; Spies et al. 1988; Sturtevant et al. 1997). A high-order polynomial or spline function may have had improved statistical fits to the data, but they would not describe the underlying processes. The use of a single function

Table 3. Equation parameter estimates for chronosequence regressions.

Chronosequence regression model	Y_0*	k*	A*	b*	Model R^2	Test $R^{2\dagger}$	df	Model F	P-value
CWD volume									
Unmanaged forest (regional)	335	0.033	185.8	0.003	0.82	0.23	4, 19	22	<0.001
Managed forest (regional)	64	0.188	29.1	0.022	0.20	0.07	4, 63	3.96	0.006
Managed (thinned <5 years ago)	65	0.198	813.1	0.001	0.57	0.76	4, 23	7.40	0.001
Managed (thinned 5 to 10 years ago)	64	0.186	17.5	0.030	0.43	0.86	4, 29	5.46	0.002
Managed (thinned >10 years ago)	64	0.177	29.7	0.013	0.49	0.58	4, 25	5.79	0.002
CWD biomass									
Unmanaged forest (regional)	113 000	0.053	60 183	0.002	0.87	0.28	4, 19	33	<0.001
Managed forest (regional)	20 200	0.209	8 050	0.019	0.24	0.27	4, 63	5.04	0.001
Managed (thinned <5 years ago)	20 700	0.217	9.69×10^9	1.53×10^{-8}	0.59	0.77	4, 23	8.28	<0.001
Managed (thinned 5 to 10 years ago)	20 500	0.205	4 344	0.027	0.54	0.83	4, 29	8.64	<0.001
Managed (thinned >10 years ago)	20 200	0.201	7 676	0.011	0.58	0.54	4, 25	8.74	<0.001

*Y_0 reflects the initial amount of CWD at stand initiation, k is a decay constant for relict CWD, A represents the asymptote or "steady state" of new CWD accumulations, and b is a shape parameter that describes how quickly new CWD accumulates.
†Reflects the ability of the regression model to fit the 10% of the data withheld from the model data set.

Table 4. Whole-model F-tests for differences between chronosequence regressions.

	Volume		Biomass		
Comparison	F-ratios	P-values	F-ratios	P-values	df
Unmanaged and managed forest (regional)	105	<0.001	125	<0.001	4, 172
Unmanaged and thinned >10 years ago	80	<0.001	102	<0.001	4, 96
Thinned <5 years ago and thinned 5 to 10 years ago	13.5	<0.001	13.8	<0.001	4, 114
Thinned <5 years ago and thinned >10 years ago	8.42	<0.001	8.89	<0.001	4, 106
Thinned 5 to 10 years ago and thinned >10 years ago	0.36	0.84	0.33	0.86	4, 120

for all data sets also allowed direct comparison among them. Differences were tested using a whole model F-test for regression curves (McRoberts 1987).

Structural characteristics

Effects of timber harvesting on structural characteristics of CWD were determined using a series of factorial ANOVAs and independent orthogonal contrasts. Although some analyses were performed for young forests (0–30 years old), the analyses are most detailed for mature forests (91–150 years old) because of larger data sets (12 managed and 10 unmanaged stands). All sample populations of structural characteristics appeared to be log-normal, so parallel log-transformed and untransformed analyses were performed. Because the results were nearly identical, only those from the untransformed analyses are presented here so that variance is in interpretable units. In addition to the categorical ANOVAs and contrast tests, nonparametric two-sample Kolmogorov–Smirnov tests were used to determine the effects of management on the distribution of logs and snags across sizes and decay states in mature forests.

Results

Chronosequence regression models

The CWD chronosequence models adequately fit the data (Table 3). For most of the regressions, the R^2 of the withheld test data was higher than or similar to that of the regression data. The test R^2s of the unmanaged data set, consistently lower than those for the regression models, were only based on two data points and both fell along the portion of the chronosequence where CWD is nearly asymptotic. The overall chronosequence for managed forests consistently had the poorest fit of all regressions, but the chronosequences based on the relative timing of thinning have better fit (Table 3). Much of the variance in the overall managed chronosequence can therefore be explained by differences in time since the most recent thinning. We consider the chronosequences to be applicable to managed and unmanaged red pine forests across the western Great Lakes states.

The unmanaged and managed chronosequences differ ($p < 0.001$) (Table 4) with less CWD throughout stand development in the managed chronosequence (Fig. 2) and with the most pronounced effects of management in young forests (Fig. 3). The CWD at stand initiation (Y_0) in managed forests is roughly 80% less than that in unmanaged forests (Table 3), and the differential effects of management continue roughly two decades after stand initiation because small-diameter slash decays rapidly, while larger-diameter fire-killed material persists (Fig. 3). Differences decrease as relict CWD decomposes and new CWD accumulates in both systems. The minimum difference between managed and unmanaged forests between 80 and 100 years of age coincides with the onset of understory reinitiation (Fig. 3). Beyond 90 years, the difference increases and the long-term accumulations of CWD (asymptote A) in managed red pine forests are roughly 85% less than those in unmanaged forests (Table 3).

Chronosequences differ among thinning regimes, with forests thinned in the past 5 years different from both those thinned between 5 and 10 years ago ($p < 0.001$) and those thinned more than 10 years ago ($p < 0.001$) (Table 4, Fig. 4). The chronosequence of forests thinned more than 10 years

Fig. 2. Comparisons of regional CWD volume and biomass chronosequences for managed and unmanaged red pine forests across the western Great Lakes states.

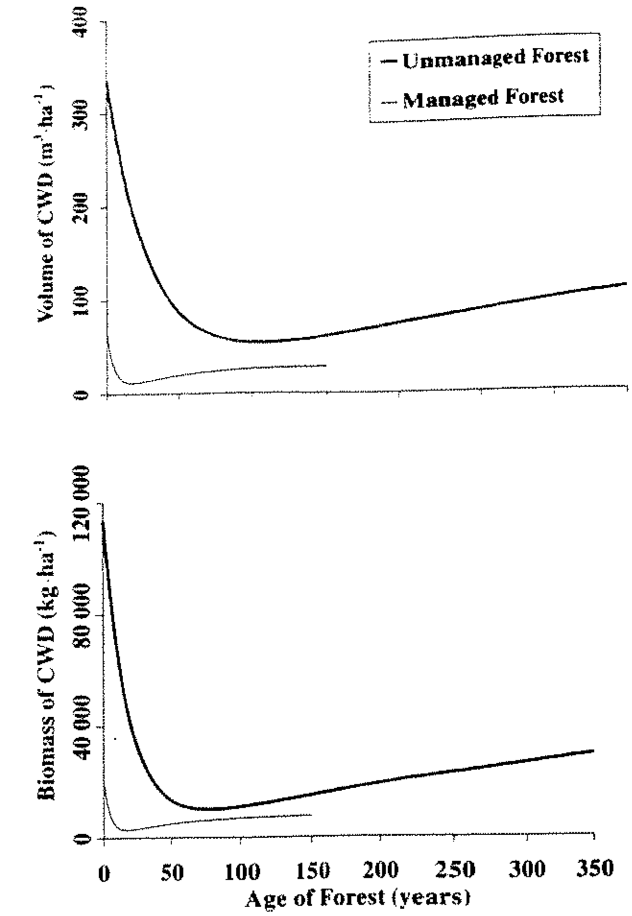


Fig. 4. Chronosequences describing effects of the time since the most recent thinning on the volume and biomass of CWD in managed red pine forests.

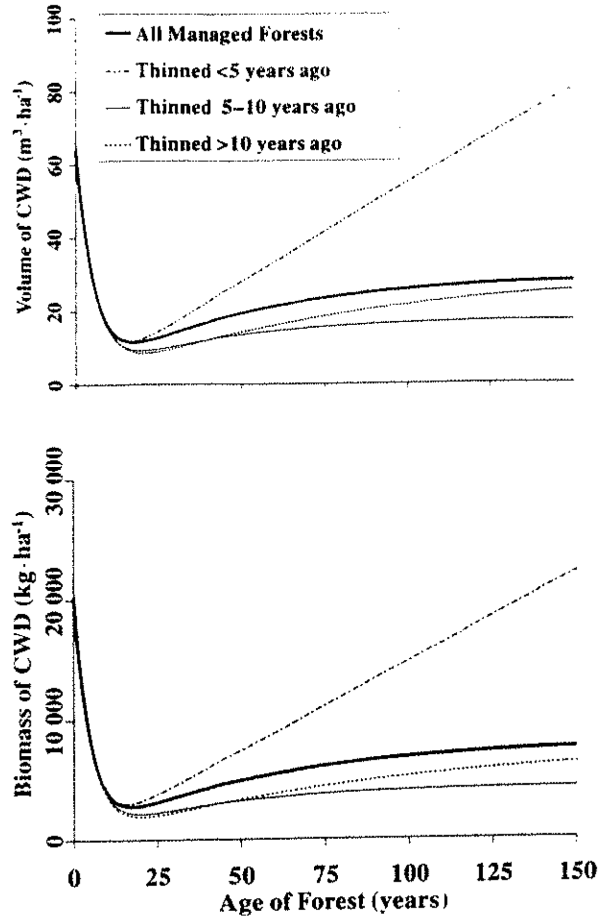
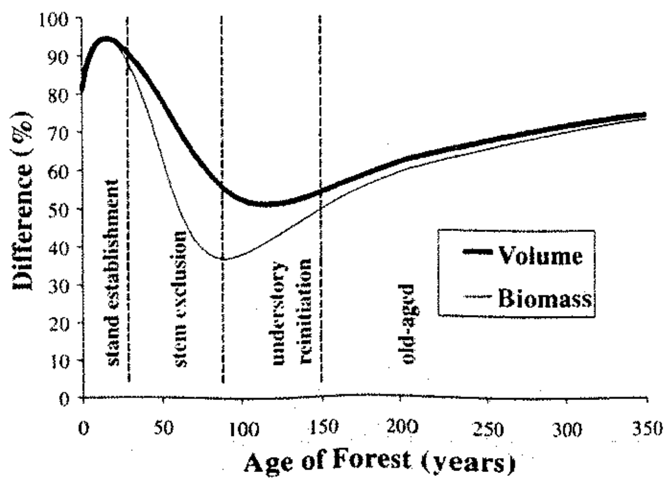


Fig. 3. Difference in the amount of CWD as a result of timber management in comparison to unmanaged forests expressed as a percent of values predicted by the unmanaged chronosequence. For example, timber management reduces the volume of CWD by 81% at stand initiation (time-zero) and 50% at 125 years. Red pine stand development stages are also indicated. The managed data only extends to 150 years, so extrapolation beyond that point is speculation based on chronosequence regression parameters.



ago is different ($p < 0.001$) than the unmanaged chronosequence. The chronosequences of forests thinned between 5 and 10 years ago and those thinned more than 10 years ago are not different ($p = 0.85$) (Table 4), but the asymptote (A) of the latter is roughly 75% larger than that for the former (Table 3). In spite of this difference, the high variance in both models obviates statistical significance. There appears to be collinearity between regression parameters A and b for the chronosequence of forests thinned less than 5 years ago, and the amount of CWD increases nearly linearly rather than asymptotically with age (Fig. 4). The linear trend, apparently due to the increasing volume of slash produced when larger trees are harvested, is difficult to describe with the monomolecular accumulation function. In spite of this, the regression converges for this data set, is repeatable, the R^2 is relatively large, and p is small.

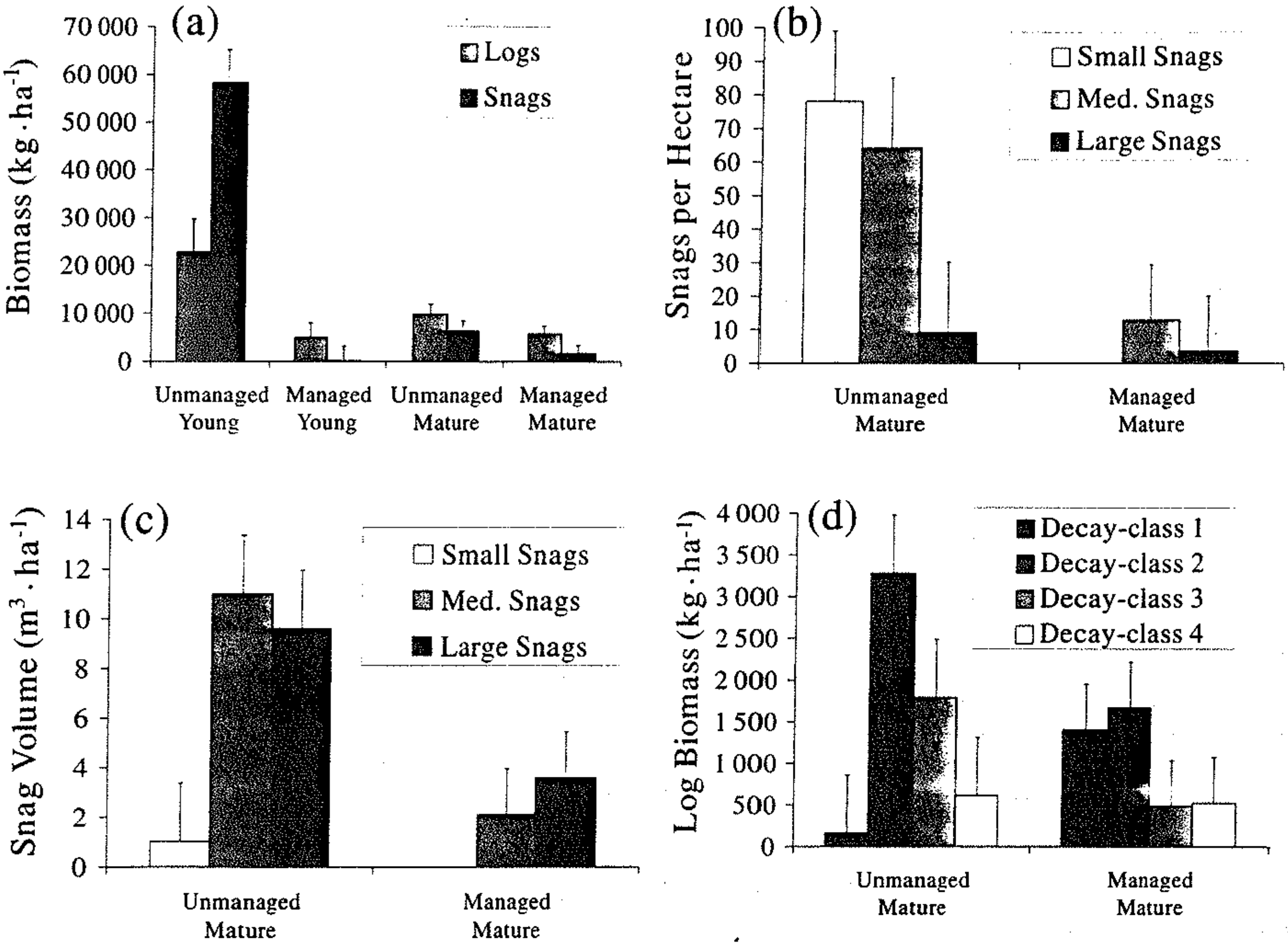
Structural characteristics

Both log and snag biomass are lower in managed than in unmanaged young red pine forests (0–30 years), with the largest difference for snags (Table 5, Fig. 5*a*). Young unmanaged forests contain nearly 800 snags per hectare with a biomass of 58 200 $kg \cdot ha^{-1}$, roughly 70% of total CWD biomass in these forests, and young managed forests only contain about 1.5 snags per hectare with a biomass of

Table 5. ANOVA concerning the effects of timber management on structural characteristics.

Young forests (stand initiation)	df	Root MSE	F-ratio	P-value
Effect (y = CWD biomass)				
Management	1	85 295	50	<0.001
Position (logs vs. snags)	1	34 404	8.13	0.007
Management × position	1	45 232	14	0.001
Error	34	12 063		
Contrast (management)				
Log biomass	1,34	28 337	5.51	0.025
Snag biomass	1,34	92 304	58	<0.001
Mature forests (understory reinitiation)				
Effect (y = CWD biomass)				
Management	1	13 827	5.46	0.025
Position (logs vs. snags)	1	11 979	4.10	0.050
Management × position	1	879	0.02	0.883
Error	42	5 915		
Contrast (management)				
Log biomass	1,42	9 154	2.40	0.130
Snag biomass	1,42	10 392	3.09	0.087
Effect (y = log biomass)				
Management	1	1 967	0.10	0.322
Log decay class	3	3 802	3.71	0.015
Management × decay class	3	2 892	2.15	0.101
Error	76	1 974		
Contrast (management)				
Log class 1 biomass	1,76	2 757	1.95	0.166
Log class 2 biomass	1,76	3 592	3.31	0.073
Log class 3 biomass	1,76	2 905	2.17	0.145
Log class 4 biomass	1,76	200	0.01	0.920
Effect (y = snag biomass)				
Management	1	5 850	17	0.0001
Snag decay class	2	6 418	20	<0.001
Management × decay class	2	4 862	12	<0.001
Error	57	1 434		
Contrast (management)				
Snag class 1 biomass	1,57	163	0.01	0.910
Snag class 2 biomass	1,57	8 972	39	<0.001
Snag class 3 biomass	1,57	999	0.48	0.489
Effect (y = log volume)				
Management	1	23.60	2.98	0.090
Log size class	2	13.56	0.98	0.381
Management × size class	2	15.02	1.21	0.307
Error	57	13.70		
Contrast (management)				
Small log volume	1,57	2.75	0.04	0.841
Medium log volume	1,57	30.76	5.06	0.028
Large log volume	1,57	7.36	0.29	0.593
Effect (y = snag volume)				
Management	1	20.37	9.35	0.003
Snag size class	2	15.53	5.43	0.007
Management × size class	2	8.83	1.76	0.182
Error	57	6.66		
Contrast (management)				
Small snag volume	1,57	2.27	0.12	0.734
Medium snag volume	1,57	19.74	8.77	0.004
Large snag volume	1,57	13.27	3.96	0.051

Fig. 5. Structural characteristics of CWD in managed and unmanaged young (stand establishment: 0–30 years old) and mature (understory reinitiation: 91–150 years old) red pine forests with standard error indicated. a) Distribution of CWD biomass between logs and snags in young and mature forests. b) Frequency and size distribution of snags in mature forests. Small snags are 2.5 to 10 cm dbh, medium are >10 to 25 cm dbh, and large are >25 cm dbh. c) Size distribution of snag volume in mature forests. d) Distribution of log biomass across the decay classes in mature forests. Decay classes represent increasing decay with decay class 1 being the least decayed (see Table 1).



150 kg·ha^{-1}, roughly 3% of their total CWD biomass. Although the difference is less for logs than for snags, young managed forests have 80% less log biomass than unmanaged forests, 5000 versus 22 800 kg·ha^{-1} (Fig. 5*a*).

Differences are less between managed and unmanaged mature forests (91–150 years) (Fig. 3), but harvesting continues to disproportionately impact snags (Fig. 5*a*). Total CWD biomass is 55% lower in managed than unmanaged forests (7600 versus 16 300 kg·ha^{-1}), but snag biomass is 75% lower. An average mature unmanaged forest contains 150 snags per hectare with a biomass of 6400 kg·ha^{-1}, roughly 40% of its total CWD, while a managed forest contains 15 snags per hectare with a biomass of 1700 kg·ha^{-1}, roughly 20% of its total CWD. Management in mature forests also affects the distribution of snags across decay states ($\alpha = 0.01$) and among size classes (Table 5). A higher proportion of snag biomass is less decomposed in managed than in unmanaged forests ($\alpha = 0.01$), and there is less large- ($p = 0.05$) and medium-sized ($p = 0.004$) snag volume (3.5 large and 13 medium snags per hectare in managed forests versus 10 large and 64 medium snags per hectare in unmanaged forests) (Fig. 5*b*). The volume of medium and large snags averages 11 and 10 m^3·ha^{-1} in unmanaged forests and 2 and 4 m^3·ha^{-1} in managed forests, respectively (Fig. 5*c*).

Because of slash inputs, the difference in log CWD is not as large as that of snags in mature managed as compared with unmanaged forests (5800 compared with 9900 kg·ha^{-1} of logs, $p = 0.130$). The relative proportion of log volume across the size range is also not different (based on Kolmogorov–Smirnov test), and only the volume of medium logs appears to be affected by management ($p = 0.028$). However, timber management affects the distribution of logs across decay states, producing a higher relative proportion of fresh logs ($\alpha = 0.01$) in comparison to a more bell-shaped distribution in unmanaged forests (Fig. 5*d*). Decay class 1 logs represent only 1.5% of the log biomass in unmanaged forests but 25% in managed forests, and are nearly an order of magnitude higher in managed than unmanaged forests (1400 versus 150 kg·ha^{-1}).

Discussion

Chronosequences

Based on the chronosequence regression constants, the amount of CWD approaches a steady state much more rapidly in managed than in unmanaged forests. In managed forests CWD reaches 90% of its asymptote (A) between 100 and 125 years of age, while in unmanaged forests it does not begin to approach a "steady state" for at least 900 to 1200 years. Although there is uncertainty in the magnitude of the regression constants, they suggest that CWD accumulation in managed forests may cease within a rotation, while accumulation continues in unmanaged forests until either a catastrophic disturbance or succession to a more shade-tolerant community occurs. This difference in accumulation has implications for the strategy of "extended-rotation" management. Unless an active approach to managing CWD is taken, managed "old growth" with all ecosystem structures and functions completely intact may not be achieved. Although the structure of living vegetation in extended-rotation managed forests may simulate natural ecosystems, the presence and role of CWD, especially large snags, are changed by commercial management in red pine forests.

Relative timing of harvests

The differences among chronosequences with time since thinning suggests that the distribution of CWD will fluctuate widely in individual stands around the overall managed chronosequence. The difference between forests thinned in the past 5 years and those thinned between 5 and 10 years ago should reflect the average magnitude of these fluctuations. The amount of CWD is high immediately following thinning, increasing with stand age as a result of harvesting larger trees. Slash decomposes rapidly in the first decade following harvest because it is mostly small in diameter (Maser et al. 1988). As the time since the thinning increases, "natural" processes increasingly control mortality and CWD begins to accumulate. However, even a single thinning affects the distribution of CWD for at least several decades.

Structural characteristics

Timber management affects the distribution and amount of snags more heavily than that of logs, especially in young forests. During a stand-replacing fire in an unmanaged red pine forest, most trees die standing and many become snags. During clear-cutting, trees are felled, logs are removed, and the residual vertical structure, both live and dead, is virtually eliminated. Although such harvesting produces slash, these inputs are significantly less than the inputs of logs following catastrophic fire.

The impacts of management on CWD structure should be at a minimum in mature forests. Harvesting affects snags more subtly in forests at this stage of development than at stand replacement. Thinning captures mortality, controls spacing, and decreases competition, all of which reduce snag production. Furthermore, any snags that develop in managed forests are commonly felled either intentionally or inadvertently during subsequent thinnings. Thinning in mature forests may have less effect on the total quantity or size distribution of logs, but because most managed stands across the region have been thinned relatively recently the biomass of fresh logs is dramatically increased.

Conclusions

Development of quantitative prescriptions for management of CWD in red pine forests across the Lake States region is premature until we have a better understanding of both the causes of variation in CWD and the ecological consequences of such variation. In addition, because prescriptions are typically applied at the stand level they must also address the land owner's objectives, the ecological processes of particular concern, and the role of that individual stand in the matrix of stands across the regional forest. Nonetheless, harvesting strongly affects CWD. Snags, with a prominent ecological role as denning and nesting sites, are especially reduced by management. The increase in fresh logs produced by thinning could be problematic because they are both a highly combustible fire fuel and a desirable substrate for many forest insect pests, including bark beetles. These problems may be temporary in individual stands, but because harvests occur continuously across the region, they are constant across the forest as a whole. Timber management reduces the amount of CWD, but before overall prescriptions are adopted to promote its abundance both its beneficial and detrimental ecological roles and its potential commercial value must be evaluated.

Finally, a disproportionate amount of the current research emphasis on CWD is being placed on old growth forests, with effects of timber management evaluated by comparing natural old growth stands with either clearcuts or managed mature second-growth stands that are younger than the old growth. Analyzing effects of management is most appropriate and informative at the same stages of stand development. Although old growth is certainly rare and ecologically important, the effects of timber management on CWD are more drastic in young than in old forests.

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