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THE IMPACT OF INTENSIVE FOREST MANAGEMENT ON CARBON STORES IN FOREST ECOSYSTEMS

Olga N. Krankina and Mark E. Harmon
Department of Forest Science
Oregon State University
Corvallis, Oregon 97331 USA

SUMMARY

People are largely dependent on forests for their construction needs, fuel, food and fiber. An increasing demand for these products has naturally lead to intensive management practices that maximize net biomass harvested. This expansion of intensive management of forest resources for timber production with the human population growth may have a profound effect on the role forests play in the global carbon cycle. First, the transition from old-growth to intensively managed second-growth forest with short rotations entails major long-term ecosystem changes including the reduction of total woody biomass. Although the biomass of living trees can be restored within a relatively short period of time, dead wood biomass takes considerably longer to reach pre-harvest levels: therefore commonly used rotations are too short for the latter part of ecosystem to recover fully. As dead trees account for 14-18% of the total woody biomass stores in a natural forest, a considerable amount of carbon can be released if this material is not replaced. Second, economically efficient, intensive forest management systems that include commercial thinning and wood salvage can further reduce the total biomass loading of second-growth forests. Long-term study of live and dead wood in thinning trials in the Pacific Northwest and in northwestern Russia suggest that intensive practices can reduce total woody biomass averaged over rotation to 10-25% that found in a natural old-growth forest. Therefore intensive forest management practices may maximize the supply of raw materials, but they may also generate a major carbon flux into the atmosphere. This flux may be significant despite the fact the land-use type (i.e., forest) remains the same. Effect of intensive forest management practices should be included in future carbon budgets and in developing forest management strategies aimed at increasing carbon storage in forest ecosystems.

INTRODUCTION

Concerns about greenhouse gas accumulation in the atmosphere have prompted extensive research of global carbon cycle (Smith, et al., 1993; Dixon, et al., 1994). Forests play a major role in this cycle as they account for the greater part of the carbon exchange between the atmosphere and terrestrial biosphere included in this analysis, but this should not change significantly the results, since durable product output ranges from 0 in biomass plantations to not more than 40% of removed timber in forests harvested for sawlog and veneer production (Harmon, et al., in review).

Table 2 Live and dead wood carbon stores across the range of site productivities in western Oregon (Mg C/ha).

Forest type (# plots)	Biomass (Mg C/ha)		Percent of dead wood
	Live	Dead	
Ponderosa Pine (4)	92.9+-8.8	18.4+-2.3	16.5
Douglas-fir (1)	375.2	62	14.2
Western Hemlock (16)	463.1+-22.6	74.5+-5.2	13.9

Live and dead aboveground tree biomass was measured in 30 experimental plots in the PNW and in 63 plots in Russia. Live tree biomass was estimated by standard procedures based on DBH and height measurements of trees in each plot and on local biomass equations (Tretyakov, 1952; Moshkalev, et al., 1984; Gholz, et al., 1979; Harcombe, et al., 1990). A biomass to carbon conversion factor 0.5 was used. As dead wood is commonly overlooked in biomass assessments and carbon budget calculations we describe the methods for this component in greater detail. Measurements of dead wood stores in the plots followed the methods procedures described in Harmon, et al. (1986, 1987). Within each plot the end diameters and lengths of each piece of dead wood >10 cm diameter and >1 m in length was recorded. All forms of coarse dead wood were inventoried including snags (standing dead), logs (dead and downed), stumps, and "blobs" of highly decayed wood. We did not inventory wood buried in the forest floor, although this can be a substantial proportion of that layer (Little and Ohman, 1988). Species and decay state of each piece were also noted. The mass was calculated by multiplying computed volume by the average bulk density of each decay class and species. Total organic mass was converted to carbon stores by assuming the carbon content of dead wood was 51% (Sollins, et al., 1987).

The Pacific Northwest plots used for this analysis are part of a series of permanent forest plots in mature and old-growth forests (Franklin and DeBell, 1988; Greene, et al., 1992; Harcombe, et al., 1990). Forest ages range from 40-500 years old, and some plots have been remeasured over a 80 year period. Our analysis concentrates on three series of plots that represent the decreasing productivity gradient in the Pacific Northwest region as one moves from the Pacific Ocean eastward (Table 2). Unlike the Russian plots, these are unmanaged forests. Plot size ranges from 0.25-5.0 ha.

The greater part of plots studied in Russia are part of large scale experiment on forest thinning started in 1928-34 and supplemented by new plots in 1968-76 at Leningrad (now St.Petersburg) Forestry Research Center (Sennov, 1984). The plots were set up in well stocked young stands (23-45 years old) of medium to high productivity. Over time plots were regularly remeasured and by now the age span of 20 to 105 years is covered by the record. Each site consists of a control plot and 1-4 thinned plots with 15-50% of the growing stock removed. The size of each plot is 0.05-0.25 ha. The Russia data set is supplemented by plots established in an

(Dixon, et al., 1991). Given that forest ecosystems store about 86% of terrestrial biosphere carbon (Olson, et al., 1985), their status and management largely determines if this part of the biosphere is a net sink or net source of carbon. To date the flux from forests appears to have been to the atmosphere, with 90 to 120 Pg of carbon released from 1850 to 1980 (Houghton and Skole, 1990). This flux is largely a response to population growth, since people are dependent on forests for their construction needs, fuel, food and fiber, and increasing demand has caused extensive deforestation and expansion of forest management. Currently, an estimated 10% of world forests is actively managed (WRI, 1990) and in the future forest management activities will expand further.

While the role of forest clearing for agriculture in adding carbon to the atmosphere has been evident for some time (Woodwell, et al., 1978; Houghton and Woodwell, 1989; Melillo, et al., 1988), there is considerable uncertainty regarding the effect of timber harvest and intensive silvicultural practices on carbon fluxes. Commonly used management practices, developed for purposes other than carbon storage and sequestration, need to be evaluated with regard to carbon cycling. Conversion of older forest to younger forest has generally been shown to release carbon to the atmosphere (Alaback, 1989; Harmon, et al., 1990; Dewar, 1991; Kershaw, et al., 1993). Intensive forest management, including financially optimized rotations, regular thinning, and wood salvage can further reduce carbon stores (Cooper, 1983). On the other hand, intensive management practices are assumed by many to increase carbon stores in forests (Kauppi, et al., 1992; Sedjo and Solomon, 1991). Extensive forest harvesting in this century has produced disproportionately large share of early successional forests with high carbon accumulation rates in all the major forest regions including boreal, temperate and tropical zones (Kurz and Apps, 1993; Kauppi, et al., 1992; Brown, et al., 1993; Solomon, et al., 1993). Although these forests may be currently significant carbon sinks, theses sinks were created by an earlier period of carbon release.

The conflicting interpretations concerning forest management practices may stem from the fact that their effect upon atmospheric carbon fluxes depends upon the ecosystem type, the types of pools considered (live only versus total ecosystem versus forest products), the initial starting conditions (old-growth forest versus bare ground), the type of silvicultural system used, and the fate of the harvested carbon. Preserving carbon stores, increasing sinks and minimizing sources associated with forests has been the focus of evolving management strategies aimed at mitigating greenhouse gas accumulation in the atmosphere (Winjum, et al., 1993; Trexler, 1993; Krankina and Dixon, 1994). These efforts may be less than successful, however, unless the effect of various management actions is examined in more detail both temporally and spatially.

The goal of this paper is (i) to review our understanding of forest biomass accumulation over succession; (ii) to assess the loss of carbon from conversion of old-growth into the second-growth forest and the impact of intensive forest management practices including harvest rotation, regeneration, site preparation and thinning on carbon stores in the second growth forest; and (iii) to evaluate the potential of management strategies to conserve and sequester carbon in forest ecosystems. Data for this assessment was primarily derived from two major forest regions of the world: the Pacific Northwest and Russia.

SOURCE OF DATA

Both the Pacific Northwest and St. Petersburg region (northwest) of Russia are among world's major sources of timber and consequently both have experienced extensive conversion of old-growth to second-growth forests. Experimental data for this study was collected in closed forest stands of medium to high productivity which are the primary subject of harvesting and intensive forest management both in Russia and in Pacific Northwest. Although this data set admittedly does not represent the average for the respective geographic regions, it allows to examine woody biomass distribution and the impact of management practices on carbon stores in the "most managed" forest types.

Live tree and dead wood carbon stores were compared for old-growth and early successional forest including clear-cut, young (10-20 years after harvest), middle aged (30-70 years after harvest), and mature second growth forest (80-120 years after harvest). Where possible the effect of thinning and salvage was assessed (Tables 1,2,3). Our focus in this analysis is mainly on the aboveground biomass accumulation of live trees and dead wood. For forested systems, trees comprise >90% of the living biomass except in the earliest stages of succession (Birdsey, 1992). The rationale for our focus on dead wood is perhaps less obvious. First, dead woody detritus is potentially a large pool of carbon (Harmon and Chen, 1991; Harmon, et al., 1993) that is very sensitive to disturbance and management actions such as salvage. Second, other detrital carbon stores are relatively stable compared to dead wood. For example, unless site preparation is extreme, mineral soils are relatively stable after harvest (Johnson, 1992). Finally, our focus on aboveground stores reflects a lack of information, rather than a lack of interest or need. There are, for example few inventories of dead wood in soil (Harvey, et al., 1981) and few biomass estimates for live roots (Gholz, et al., 1979). We therefore acknowledge that our live and dead wood carbon estimates could be low as much as 20% (the upper limit assumed for the proportion of below-ground biomass).

Comparison of management scenarios is based on average amount of carbon stored above ground over an indefinite number of rotations (Winjum, et al., 1993). Carbon stores in forest products are not

Table 1 Aboveground carbon stores at different successional stages in PNW and in Russia.

Successional stage	Units	PNW		Russia	
		live	dead	live	dead
Oldgrowth	Mg C/ha	375	62	66	15
	%	85.9	14.1	81.9	18.1
Clear-cut	Mg C/ha	1	188	1	21
	%	0.3	99.7	2.3	97.7
Young	Mg C/ha	--	--	17	1
	%			95.1	4.9
Middle age	Mg C/ha	--	--	89	3
	%			96.8	3.2
Mature	Mg C/ha	229	22	100	7
	%	92.8	7.2	93.6	6.7

old-growth spruce stand and in a windthrow area by the St. Petersburg Forest Academy and by 4 temporary plots set up by the authors on recent clear-cut (Tables 1,3).

Table 3 Effect of natural disturbance and thinning on carbon stores in Russia (Mg C/ha).

Stand category	Plot (salvage level)[1]	Treatment	Live	Dead
Natural disturbance	VALYA (0)	90% windthrow	26	25
		30% windthrow	70	11
		control	88	8
Mature	1 (2)	thinning	55	1
		control	127	4
	2 (2)	thinning	56	5
		control	73	3
	12 (1)	thinning	102	5
		control	135	4
	13 (2)	thinning	108	4
		control	151	2
	20 (1)	thinning	110	6
		control	136	4
	21 (1)	thinning	120	5
		control	122	5
	28 (0)	thinning	75	10
		control	109	9
Middle age	1 (0)	thinning	68	7
		control	78	3
	2 (0)	thinning	53	5
		control	67	4
	8 (2)	thinning	43	1
		control	53	1
	10 (1)	thinning	58	6
		control	99	4
	11 (2)	thinning	116	3
		control	147	4

[1] Salvage level: 0 - no salvage, 1 - moderate salvage, 2 - thorough salvage.

Despite the large amount of data from our study areas on live and dead wood stores, we were unable to find data values for many situations, such as poorly regenerated areas, biomass plantations, areas with heavy fuel reduction, etc. We therefore used a simple simulation model (Harmon, et al., 1990) to estimate carbon stores in these unsampled situations. For live biomass, the model was calibrated to mimic yield tables values for moderately high site quality for both regions. Live production was assumed to reach a peak at 45 years for both regions, and have levels of 2 and 4.4 Mg C/ha year for Russia and the Pacific Northwest, respectively. Dead wood inputs were estimated assuming that tree mortality was 0.3% of live biomass. Inputs via disturbances such as fire or timber harvest were estimated from the proportion of live biomass killed and removed by the appropriate disturbance. Dead wood decay rates were assumed to be 2%/year for both regions. Model results are presented in absolute terms (M4g C/ ha) and in relative terms as a percentage of the estimated ecosystem maximum potential carbon stores of the site. This was calculated by assuming that old-growth forests would have the maximum combined live and dead wood stores. We realize few real forests have carbon stores approaching this maximum, and that even in a natural setting the actual stores would lie below this maximum due to disturbance. Nonetheless, the concept of a maximum potential store is useful to compare the relative effect of various silvicultural treatments and to compare forests with different levels of productivity stores.

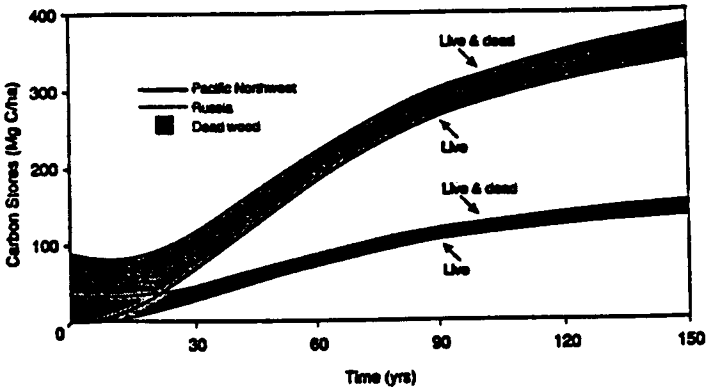

Figure 1 Changes in live and dead wood carbon stores following clear-cut harvest

RESULTS AND DISCUSSION

Successional Pattern of Woody Biomass Accumulation

Conversion of old-growth forest into second-growth significantly reduces carbon stores in both the Pacific Northwest and Russian forests. Living tree biomass is restored to its maximum level after 150-200 years (Figure 1). If one considers the average carbon stores in the living trees over common commercial rotations of 60-100 years, then the managed forest contains 25-45% of the potential (Figure 2). These calculations assume "the best case" management scenario including sustainable growth rates and regeneration immediately after harvest. In "real life" site productivity frequently decreases and reforestation is delayed resulting in even lower average carbon stores.

Although the general pattern of accumulation of live biomass is well known, the same can not be said of dead wood. In many older reviews (Triska and Cromack, 1979; Schlesinger, 1977) it was assumed that dead wood biomass paralleled live biomass. This is, however, rarely the case in secondary succession of forests (Gore and Patterson, 1986; Harmon, et al., 1986; Spies, et al., 1988). To understand the successional patterns of dead wood accumulation one must consider three phases of succession: disturbance, recovery, and old-growth (Tables 1,3).

By far the largest amount of dead wood occurs in recently disturbed forests (Harmon and Chen, 1991). While there are few published values of dead wood stores immediately following fires, we can make an upper estimate from living biomass assuming little large

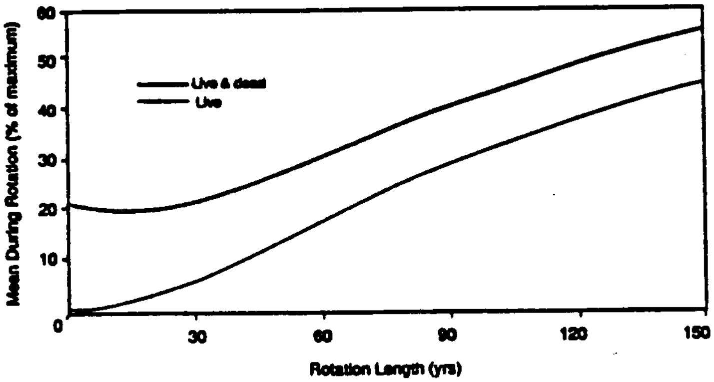

Figure 2 Effect of rotation length on the average carbon stores of live and dead wood

woody material is consumed by fires. This would indicate that in conifer forests carbon stores in dead wood immediately following a fire would range from 70-380 Mg C/ha. The decomposition of this woody detritus has not always been included in assessing the effects of forest fires on the global carbon budget, but Auclair and Carter (1993) indicate these postfire losses often exceed the mass consumed by the fire by an order of magnitude.

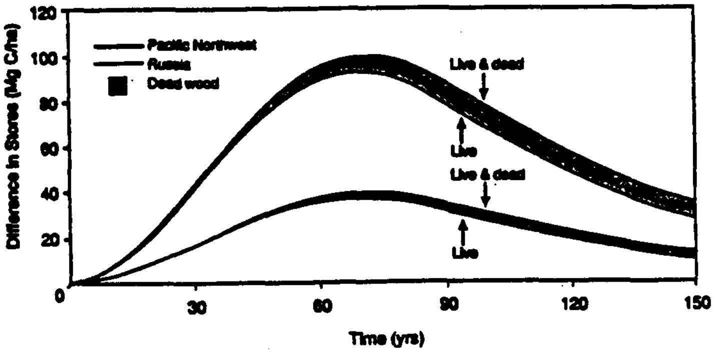

Figure 3 Effect of delayed reforestation on live and dead wood carbon stores.

Timber harvest can also elevate the level of woody detritus in forests (Figure 3). Therefore, we assume delayed reforestation doubles the time required to reach peak production following harvest; and, results expressed as the difference between a stand reaching peak production in 45 versus 90 years. Except in the most intensive harvesting regime where entire trees are removed, 10-30% of the boles biomass is left on site (Harmon, et al., in review). Our estimates of the dead wood mass added by harvest in the Pacific Northwest indicate that in most situations, dead wood mass is elevated by a factor of 1.5-2.8 during harvest. A considerably larger proportion of biomass is left during harvest in Russian forests, often in the form of logs left on the site or as abandoned log decks.

Windthrow is a type of disturbance that transfers biomass from live into dead wood pool without immediate carbon loss. It is fairly widespread in Russia: in 1990 it was reported on 30,000 ha while the actual extent can be even greater (Krankina, et al., in review). To compare carbon dynamics in forests regenerating after natural disturbance and after harvest we studied forest stands twelve years after a severe wind storm which knocked down up to 90% of trees some 200 km east of St. Petersburg. At that time dead wood stores in severely hit areas were 3-4 times greater than in undisturbed forest and live tree biomass was about equal to that of dead wood (Table 3). The total biomass was 2-3 times higher compared to areas regenerating after clearcutting (Table

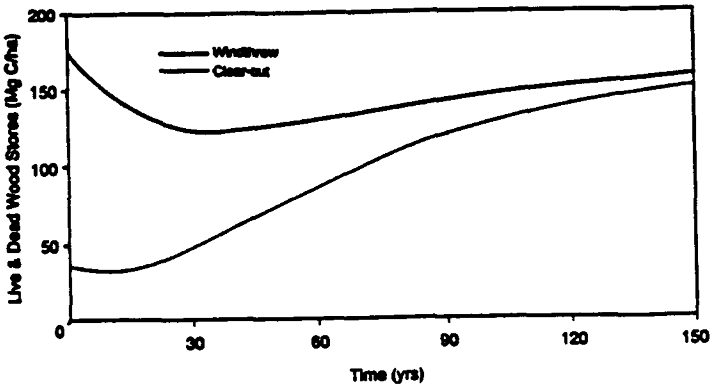

Figure 4 Comparison of live and dead wood carbon stores in forest stands disturbed by clear-cut and windthrow

1). This analysis indicates that, compared to harvesting, a natural disturbance regime should maintain higher levels of dead wood and total biomass stores (Figure 4).

The recovery of dead wood stores to old-growth levels depends upon the decay rate and time required to restore input or mortality to old-growth rates (Harmon, et al., 1986; Harmon and Chen, 1991). Unlike fine litterfall rates it can take over a century to return dead wood input rates to old-growth levels and only after that will dead wood stores stabilize. The accumulation of dead woody detritus at the Cascade Head site provides an interesting example of how ecosystem carbon stores can increase even when the living portion has reached a "steady-state". These forests were severely disturbed by fire approximately 140 years ago (Harcombe, et al., 1990) and accumulation of above-ground living carbon stabilized at 600 Mg C/ha 120 years after the fire. Inputs from tree mortality did not stabilize until the forests reached their maximum live biomass; therefore the accumulation of dead woody detritus has continued at the rate of 1-2 MgC/ha year during the 120-140 year period. Based upon the decay rates observed for this forest we anticipate this increase may continue for another century. If this is typical of forests in general, then many forests with stable live biomass may have the potential to accumulate a substantial amount of additional carbon (Harmon and Chen, 1991).

By controlling the rotation length, forest managers can make dead wood a source or a sink of carbon to the atmosphere. Today the length of rotations is based upon short-term economic gain and the accumulation rate of live biomass. This system leads to a phase of succession when dead wood stores are at a minimum (Spies, et al., 1988). By lengthening rotations past economic maturity, mortality rates are increased to the point where dead wood begins to accumulate (Figure 4). Dead wood stores can also be increased in the short term by greatly shortening the rotation to decrease the time since the last pulse of dead wood added by harvest. Unfortunately this also has the effect of decreasing the amount of carbon stored in live biomass, with the overall effect of reducing stores (Figure 2).

The stores of dead wood in old-growth forest is highly variable with a range of 18-75 Mg C/ha in the Pacific Northwest (Table 2), and 15-36[1] Mg C/ha in a Russian old-growth forest. To a large degree these differences in stores appear to correspond to the productivity of the different forests. For example, there is almost a 5-fold difference in forest live biomass and productivity as one moves eastward from the Pacific Ocean across the Cascade Range of Oregon (Table 2). This results in a similar change in dead wood stores. Expressed as a fraction of total wood stores (live + dead), dead wood makes up between 14-18% of the total of these forests. What is perhaps even more surprising is that dead wood makes up a similar amount (18%) of the total wood stores in Russian forests. This may be a common proportioning for cool conifer forests, and therefore useful to estimate potential dead wood stores for a wide range of site productivities.

Our Russian estimates of potential carbon stores agree well with tree biomass and dead wood values for southern taiga reported by N.I. Basilevich (1986). This could be expected since both studies were designed to assess vegetation biomass storage and production potential rather than regional averages. Interestingly, this is

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[1] The upper value is an estimate based on yield tables for high site quality and the dead/live wood ratio of the old-growth stand that was measured.

one of few occasions when dead wood stores are reported and the results support our estimate of dead wood proportion in total biomass stores at about 20%.

Stability of Dead Wood Stores

To sensibly manage dead wood in the context of carbon stores, one needs to determine if these pools are decreasing, increasing, or stable. Unfortunately this pool is rarely inventoried, let alone monitored, so we must rely on approximations to assess "stability". The most direct method would be to compare current stores to a site with old-growth values (Table 1). For example, in Oregon the old-growth Douglas-fir forest contained 40 Mg C/ha more dead wood than the mature forest indicating an average accumulation rate of <0.4 Mg C/ha year or about half the rate of live biomass accumulation over the same period. A similar comparison for the Russian forests indicates an increase in stores of at least 8 Mg C/ha, but unfortunately the site quality of the mature forest used in this comparison far exceeds the old-growth site. A method that avoids these problems is to estimate the potential stores based on the ratios of dead and live wood in old-growth forests and compare this to the actual stores. This would indicate that the mature Russian forest has the potential to store an additional 18 Mg C/ha in dead wood. This estimated store also indicates that the thinned and salvaged stands are far below their potential dead wood stores.

Yet another method to test if dead wood stores are stable is to calculate the decay rate needed to keep the current store in balance given the input or mortality rate. If the dead wood pool is in steady-state then:

$$k=I/M$$

where k is the decay rate, I is the input rate, and M is the mass of dead wood stores (Olson, 1963). For most cool, conifer ecosystems a decay rate > 3%/year would be exceptional (Harmon, et al., 1986; Harmon and Chen, 1991). In the case of the Cascade Head western hemlock stands, this index indicates (shows) these stands are unlikely to be stable as a decay rate of 4%/year (or about 4 times the measured rate) is required to balance inputs (Grier, 1978)., In Russia the average mortality input in mature stands over the last 50-60 years was 53 MgC/ha or 0.96 Mg C/ha per year. To reduce this input to current stores of 7.2 MgC/ha it would take a decay rate of 13%, also far in excess of the expected range.

Regeneration/Afforestation

Delays in regeneration can have a large impact on carbon stored in live and dead wood (Figure 3). Assuming that poor regeneration would result in a doubling of the time to reach peak production (i.e., 45 to 90 years) we used the model to estimate difference in carbon stores. These differences are as much as 40 and 100 Mg C/ha for the Russian and Pacific Northwest ecosystems, respectively. On a relative basis this amounts to approximately 25% of the maximum carbon stores of these forests. Although the majority of the difference is caused by lower live biomass, about 10% of the difference is caused by reduced dead wood stores. Averaged over a 100-year rotation, the loss of carbon due to delayed regeneration is about 15% of maximum potential carbon store.

This simulation indicates that perhaps the single most important contribution that intensive management could play in terms of increasing carbon stores in forests is to increase the rate harvested forests are regenerated. In Russia today, a large proportion of clear-cut areas are not returning to trees adequately. As of 1988, 8.4 million ha of unregenerated clear-cut and 137 million ha of low-grade hardwood regeneration have accumulated in Russia (Anonymous, 1990). The total area of productive forest land technically suitable for plantations in Russia is 94.0 million ha (Krankina and Dixon, 1994).

There are also regeneration problems in the Pacific Northwest where better technological and legal mechanisms exist. For example, the Oregon Forest Practices Act has required regeneration within 5 year since the early 1970's. This has lead to the increased use of nurseries to raise seedlings that are then planted in harvested ares. Despite this, in Oregon there are currently 1.69 X 105 ha of non-stocked forest land, or about 9% of the total forest land base (Haynes, 1986). Intensive management is required to convert these lands back into significant production.

There has been considerable interest in afforestation, with emphasis on lands currently without forests as a means to sequester carbon (Sedjo and Solomon, 1991). We think the emphasis should be on understocked or poorly regenerated lands rather than lands where forests are marginal ecosystems. In the Pacific Northwest, for example, yield tables indicate that planting forests on marginal land might result in an average uptake of 1-1.5 Mg C/ha year or a maximum storage of 50-75 Mg C/ha in 50 years. In contrast, converting a poorly stocked area of high site quality currently dominated by shrubs back into trees, could result in an average uptake of 3-4 Mg C/ha year or a maximum storage of 150-200 Mg C/ha in 50 years. Therefore, for an equivalent impact one would need to treat twice the area of marginal forest land.

Site Preparation

Although increasing the rate of regeneration success can increase carbon stores in live trees, many of the practices associated with this activity such as broadcast burning may reduce stores in detrital pools. The amount of coarse woody detritus consumed by a broadcast fire is highly variable, but in Pacific Northwest forests a 50% reduction would be extreme (Reinhardt, et al., 1991; Sandberg and Ottmar, 1983). A larger fraction of wood is consumed in areas where woody detritus is yarded, piled and then burned. The latter activity is often justified as a step to increase regeneration success and reduce planting costs (Cramer, 1974). The degree this practice decreases in detrital stores and impacts the overall carbon flux depends

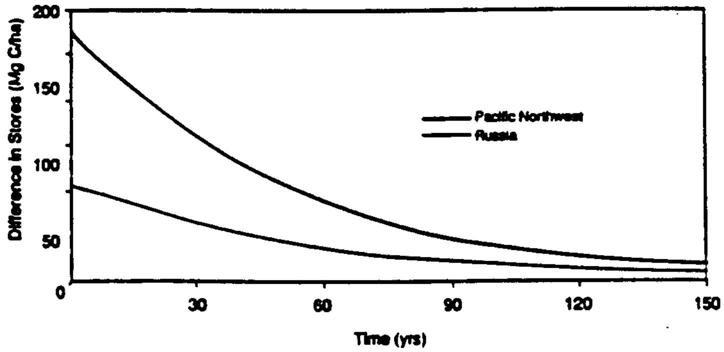

Figure 5 Effect of burning dead wood in the course of site preparation on carbon store

upon the rate this material decomposes. In the case of woody detritus, each 10% reduction in mass by burning is approximately equivalent to 5-10 years of decay. In contrast, each 10% reduction in forest floor mass by burning is equivalent to 0.5-1 years of decay. So while it is safe to assume fuel reduction of forest floors results in a similar temporal release as decay, for woody detritus this assumption may be less useful. It is possible to increase carbon stores by not burning woody detritus, because in the time it takes to decompose other pools such as live trees may begin to store carbon. We estimated the difference in carbon stores over succession for areas with no reduction in dead wood and a 50% reduction associated with site preparation. In the Pacific Northwest, the difference could be as much as 55 Mg C/ha in the earliest stages of succession (Figure 5). Therefore, we assumed 50% of the coarse wood was combusted; and, results expressed as a difference between a stand with versus without wood removal. Averaged over a 60 year rotation the differences could be 14 to 36 Mg C/ha for Russian and the Pacific Northwest regions, respectively. These values are about 10% of the maximum potential carbon stores of these forests.

Stand Thinning

Precommercial and commercial thinning is a common practice in managed forests to enhance the productivity of individual trees. This is not the same, however, as increasing stand level productivity. Thinning generally increases economic productivity by allowing larger more valuable individuals to grow faster. Additionally by harvesting smaller, suppressed trees before they die and begin to decay, thinning increases economic yields. But neither of these processes increase the amount of carbon removed from the atmosphere.

The effect of precommercial thinning is best illustrated in the Pacific Northwest where studies have been conducted since the 1920's. Precommercial thinning resulted in substantially less carbon accumulation in high site quality western hemlock (Hoyer and Swanzy, 1986) and Douglas-fir stands (Reukema and Smith, 1987), with thinned stands containing 15-55% of the stores of unthinned stands even after several decades of post-thinning growth. At 22-29 years old the thinned stands contained 17-140 Mg C/ha less carbon than unthinned stands, equivalent to 4-30% of the maximum potential carbon store. There are, however, cases where precommercial thinning of overstocked young stands ("thickets") has significantly improved production. For example, production of Douglas-fir on poor quality land increased for the first 53 years with increased initial spacing of up to 4 m (Reukema, 1979). In this case, total production nearly doubled from 55 to 100 Mg C/ha. Current practices in the Pacific Northwest are to plant or precommercially thin stands to a spacing of at least 2.7 m (Cafferata, 1986). Based upon studies of initial stocking levels on total wood production, this could be reducing carbon uptake in young stands by at least 15%.

The effect of commercial thinning can readily be seen in the results of the Russian thinning trials (Table 3). Repeated commercial thinning reduced living tree carbon stores by 2-57%. Depending on salvage, dead wood stores can also be reduced to smaller or greater degree due to lower mortality rates in thinned stands. Commercial thinning studies in the Pacific Northwest indicate a similar effect of reducing live stores of carbon. In four studies examining growth over a 15-49 year period, live carbon stores of thinned stands were 45% to 84% of the unthinned stands

(King, 1986). As the age at last measurement ranged from 49 to 67 years old, these stands would be considered of rotation age. Thinning in the Pacific Northwest reduced carbon stores 5-25% of the maximum potential carbon stores for these sites. Interestingly, there has been a long standing debate in the Russian literature concerning the optimal density of trees to maximize stand level productivity (Sennov, 1984; Pshenichnikova, 1989). The result of the Russian study and North American works appears to be that, within reasonable limits, the greater the stocking, the greater the overall production of a stand (Sennov, 1984). Regular thinning brings down biomass accumulation curve in the same manner as delayed regeneration (Figure 3). Our estimates agree with the results of other studies of the impact of thinning on carbon storage (Cooper, 1983; Dewar and Cannell, 1992).

In addition to the response of the trees themselves to thinning, one must also consider the fate of the harvested trees and the creation of detritus caused by thinning. In precommercial operations, all the thinned trees are added to the detrital system. In commercial thinning larger trees are generally removed, but in Russia where access can be a problem, larger trees are often left on the site. In plots studied 10 years after such thinning the dead wood stores were nearly double those in control plots (Table 3). While leaving this slash may increase the flux to the atmosphere, it may also store carbon longer than forest products such as paper or fuels.

Use of Wood

Net effect of silvicultural practices depends on the use of harvested wood. Thinning harvests produce less sawlogs and more products with shorter lifetime (pulpwood and firewood) than the final harvest. Most salvaged dead wood is used for firewood so its carbon is released to the atmosphere within a year. Wood salvage for fuel is widely spread in the easily accessible forests, especially in Russia where the rural population almost entirely depends on firewood for its heating needs. It is estimated that worldwide about half of harvested wood is used as fuelwood (FAO, 1990). In intensively thinned and harvested forests dead wood stores are kept at extremely low levels throughout the rotation.

It is becoming a common practice to "credit" biomass fuels as a sink of carbon (Dixon, et al., 1994). We suggest that whether these fuels are a sink or source of carbon depends strongly on the context of the system being evaluated. In the case of biomass plantations on non-forested land, biomass fuels may be considered a sink (as the carbon stores per area increases) and as well as an offset to the release fossil fuels. On the other extreme would be the process of converting mature to old-growth forests to a biomass plantation. In this case, the short rotation biomass plantation would store less carbon and therefore would be a net source, until the fossil fuel carbon saved is equivalent to the net loss in ecosystem storage. This time period is likely to be in the order of 150 years (5 30-year rotations in the case of the Pacific Northwest or 3 rotations 60 years each in Russia). Unless this distinction is recognized, then conversion to biomass fuels may actually increase rather than decrease atmospheric carbon. As old-growth to second-growth conversion causes permanent loss of carbon from the system, the harvest of old-growth forests should probably be viewed as resource extraction, like fossil fuels, rather than part of renewable resource management.

Forest Management Strategies to Increase Carbon Stores

Table 4 Loss of carbon from forest ecosystems caused by natural disturbance and management practices.

	Relative loss (%)[a]	Absolute loss (MgC/ha)	
		PNW	Russia
Natural disturbance (250 year rate of return)	13	57	19
Harvest rotation 60-100 yrs	60-75	262-328	86-107
Harvest rotation 60-100 yrs + sitepreparation + thinning + salvage	75-90	327-391	107-129
Harvest rotation 100 years + delayed regeneration	75-79	329	113

[a] Percent of maximum potential carbon store: 437 MgC/ha for Pacific Northwest and 143 MgC/ha for Russia.

Old-growth forest conservation appears to be the most promising measure since all commonly used forest management practices discussed above with the exception of plantations, reduce carbon stores in woody biomass. Assuming that undisturbed old-growth forest contains 100% of potential carbon store, natural disturbance with 250 year rate of return will reduce average carbon store by 13% (Table 4). This is a minor reduction compared to harvest rotation which causes the loss of 60-75% of potential carbon store. Combined with high intensity management system (i.e., 60-100 year harvest rotation, site preparation and thinning) the store of carbon is reduced to 10-25% of the potential. This estimate agrees with the results of other studies and geographic areas (Cooper, 1982; Dewar and Cannel, 1992; Kershaw, et al., 1993). From the perspective of carbon storage low intensity management with longer rotations and delayed reforestation is not different from intensive management.

The potential of forest conservation to protect existing carbon stores can be dramatically different depending on the geographic region. Some of the most productive conifer forests in the world are located in Pacific Northwest (Fujimori, 1971) and the total carbon loading in there appears to be significantly higher than in Russia. This is reflected both in our experimental plots (Table 1) and in available forest inventory data. Average aboveground live tree biomass in the northwestern region of Russia is 38 Mg C/ha compared to 86 Mg C/ha in the PNW (Anonymous, 1990; Haynes, 1986) with the PNW per hectare capacity exceeding that of Russia by a factor of 2.5.

Relative to old-growth forest preservation for the purposes of carbon storage other management options have significantly smaller potential. For example, to offset the loss of carbon from conversion of 1 ha of old-growth forest, harvest rotation has to be extended from 60 to 100 years on 5 ha, or reforestation provided on the same area, or site preparation, thinning and salvage avoided. Another advantage of forest protection is that the benefit is realized immediately in contrast to afforestation projects that take decades to reach maximum sequestration rates and centuries to reach their potential carbon store.

CONCLUSIONS

Currently about 10% of world forests is actively managed (WRI, 1990). As the demand for forest products continues to grow the area of managed forest will increase, and so will the impact of forest management on carbon balance. The loss of carbon from conversion of old-growth forest into intensively managed second growth forest with short rotations is substantial while land-use type (i.e., forest) remains the same. As forest management practices expand into natural forests this carbon flux is increasingly important on the global scale. While necessary to meet the needs of human population, intensive forest management for maximum biomass production reduces carbon stores in forest ecosystems to 10-25% of the potential level. Effect of intensive forest management practices should be included in future carbon budgets and in developing forest management strategies aimed at increasing carbon storage in forest ecosystems.

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