Determining Landscape-Level Carbon Emissions from Historically Harvested Forest Products

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Abstract: *Resources have been developed in the literature to enable landowners to estimate the carbon sequestration timeline of forest products derived from their land. These tools were used here to estimate sequestration and emissions related to harvests carried out in Ravalli County from 1945 to 2007. This county-level accounting of product carbon release can later be combined with county-level estimates of growth and emissions from fire and other sources to provide landscape-level insights into relationships between forest carbon exchange and processes like harvest and fire.*

Keywords: Forest Products, Carbon Sequestration, Carbon Accounting

Introduction

It is broadly recognized that durable forest products may represent significant storage of forest carbon. Although the sum of stored product carbon and re-growing stand carbon may take many years to reach pre-harvest stand storage levels (Harmon et al., 1990), harvest products nevertheless delay the release of carbon from disturbed stands. Accurate assessment of the relationship between forest dynamics and the carbon cycle must account for the storage of forest carbon in products that are either in use or in landfills (Schlamadinger and Marland, 1996). Efforts are underway in the Rocky Mountain Research Station to monitor several interrelated components of landscape-scale forest carbon dynamics by combining remote sensing with carbon-tracking tools developed to help individual landowners register sequestration related to management. These tools, detailed by Smith et al. (2006), include heuristics for estimating the timeline of decay for forest products in various regions within the United States. Since decay of old forest products can contribute to current emissions, it is important to understand historical harvest trends of areas being monitored. The goal of this paper is to outline a strategy for combining product disposition heuristics such as those published by Smith et al. (2006) with county-level historical timber harvest information to develop estimates of recent emissions stemming from historical harvest products. The resulting estimated rates of product carbon release will be combined in future work with estimated effects of ecosystem processes such as growth and disturbance to provide a fine-scale picture of forest carbon exchange related to landscape dynamics.

Much regional and national carbon cycle monitoring relies upon what is called the "stock change" approach – tracking inventory-based estimates of ecosystem carbon stores

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In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. 2009. 2008 Forest Inventory and Analysis (FIA) Symposium; October 21-23, 2008: Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 1 CD.

over time – plus accounting for carbon sequestered in products (e.g. Skog and Nicholson, 2000; Heath et al., 2003; Woodbury et al., 2007). Stock change approaches consider the competing factors that affect ecosystem carbon storage only in aggregate: stable stock levels may actually imply stasis, or they may imply offsetting trends in factors such as fire, growth, and harvest. An alternative monitoring approach that does address the differential effects of growth and harvest was described by Smith et al. (2006) to help landowners understand and potentially register gains in carbon sequestration due to their management decisions. Like Birdsey (1996), Smith et al. (2006) provided "look-up" tables that give regional averages for ecosystem carbon accumulation and product carbon sequestration. Work is underway at the US Forest Service's Rocky Mountain Research Station to produce similar look-up tables for other processes such as fire.

While stand-level look-up tables address dynamics such as the role of disturbance that are ignored in stock-change approaches, stand-level approaches cannot work at broader scales unless important details are known about every stand in the forest. Choosing the appropriate cell in any given look-up table, for example, requires that the region, species group, and growing stock volume or age be known. Additionally, one must know how and when disturbance has reset carbon densities among different stand pools in each stand. Remote sensing can provide estimates of these stand parameters across large areas. Satellite-derived species group maps are available across the country (Ruefenacht et al., 2008), volume and age estimates can be mapped when inventory and satellite data are combined (Kimes et al., 1996; Healey et al., 2006), and many disturbances can be mapped with a high level of precision (Cohen and Goward, 2004).

Like other approaches for tracking forest carbon dynamics, efforts to use remote sensing in conjunction with stand-level look-up tables depend upon accurate assessment of the disposition of product carbon. Historical harvest monitoring data are available at the county level in timber-producing areas throughout the United States. One source of this harvest information is Timber Product Output (TPO) monitoring, which is carried out nationally on behalf of the U.S. Forest Service's Forest Inventory and Analysis program (FIA). These data contribute to national timber harvest analyses presented in RPA reports (Forest and Rangeland Renewable Resources Planning Act, 1974 -- see Smith et al., 2004). Using historical harvest data along with product disposition rates published by Smith et al. (2006) and some assumptions about how these rates have changed over time, one may estimate recent rates of product carbon emissions at the county level. This paper details how such estimates may be made, using Ravalli County in western Montana as an illustration.

Methods

Smith et al. (2006) provided heuristics for the timing and movement of product carbon as it passes from the "in use" pool into landfills and finally into the atmosphere. Table 1 reprints these heuristics for the northern Rocky Mountain region. The methods described here allow product dynamics implicit in these tables to be combined with historical records of annual harvest volume to track how much carbon is released each year from

Table 1: Product Disposition Rates from Smith et al. (2006) with relevant derived annual changes.

Years after production	In use	Landfill	Energy	Emitted without energy	Year-on-year emission	Year-on-year disposal
	----------- Fraction of original harvest			-------	----- Annual Change -----	
0	0.704	0	0.209	0.087	0.087	0.087
1	0.664	0.019	0.223	0.094	0.007	0.026
2	0.628	0.036	0.235	0.101	0.007	0.024
3	0.595	0.051	0.247	0.107	0.006	0.021
4	0.567	0.065	0.256	0.112	0.005	0.019
5	0.541	0.077	0.265	0.118	0.006	0.018
6	0.517	0.088	0.273	0.122	0.004	0.015
7	0.495	0.098	0.28	0.127	0.005	0.015
8	0.474	0.107	0.287	0.131	0.004	0.013
9	0.455	0.116	0.294	0.135	0.004	0.013
10	0.438	0.124	0.3	0.139	0.004	0.012
11	0.425	0.1296	0.304	0.142	0.003	0.0086
12	0.412	0.1352	0.308	0.145	0.003	0.0086
13	0.399	0.1408	0.312	0.148	0.003	0.0086
14	0.386	0.1464	0.316	0.151	0.003	0.0086
15	0.373	0.152	0.32	0.154	0.003	0.0086
16	0.3644	0.1558	0.3226	0.1562	0.0022	0.006
17	0.3558	0.1596	0.3252	0.1584	0.0022	0.006
18	0.3472	0.1634	0.3278	0.1606	0.0022	0.006
19	0.3386	0.1672	0.3304	0.1628	0.0022	0.006
20	0.33	0.171	0.333	0.165	0.0022	0.006
21	0.3234	0.1738	0.335	0.167	0.002	0.0048
22	0.3168	0.1766	0.337	0.169	0.002	0.0048
23	0.3102	0.1794	0.339	0.171	0.002	0.0048
24	0.3036	0.1822	0.341	0.173	0.002	0.0048
25	0.297	0.185	0.343	0.175	0.002	0.0048
26	0.2918	0.187	0.3444	0.1768	0.0018	0.0038
27	0.2866	0.189	0.3458	0.1786	0.0018	0.0038
28	0.2814	0.191	0.3472	0.1804	0.0018	0.0038
29	0.2762	0.193	0.3486	0.1822	0.0018	0.0038
30	0.271	0.195	0.35	0.184	0.0018	0.0038
35	0.248	0.204	0.356	0.192	0.0016	0.0034
40	0.229	0.211	0.36	0.2	0.0016	0.003
45	0.213	0.217	0.364	0.207	0.0014	0.0026
50	0.198	0.222	0.367	0.213	0.0012	0.0022
55	0.185	0.227	0.369	0.219	0.0012	0.0022
60	0.174	0.231	0.371	0.225	0.006	0.01
65	0.163	0.235	0.372	0.23	0.005	0.009
70	0.154	0.238	0.373	0.235	0.005	0.008
75	0.146	0.241	0.373	0.24	0.005	0.008
80	0.138	0.244	0.373	0.244	0.004	0.007
85	0.131	0.247	0.373	0.249	0.005	0.008
90	0.124	0.25	0.373	0.253	0.004	0.007
95	0.118	0.253	0.373	0.256	0.003	0.006
100	0.112	0.255	0.373	0.26	0.004	0.006

products produced in each previous year. This accounting of product carbon release depends upon good records of historical harvests and upon systematic tracking of the carbon in each year's product cohort as it progresses through the timeline of disposition described in Table 1. Both of these accounting components are discussed below.

Underlying Timber Product Output Data

Timber Product Output (TPO) studies are conducted nationally for FIA to estimate industrial and non-industrial uses of roundwood across the United States (e.g. White et al., 1980; Keegan et al., 2001). All primary wood-using mills in each state are periodically canvassed regarding the amounts, types, and origin of the wood products they use. Logging utilization studies that are also carried out for FIA provide an important link between this industrial data and inventoried volume.

TPO data showing annual removals in board feet (bf) from Ravalli County in four points in time (1988, 1993, 1998, and 2004) were the starting point for a county-level harvest timeline. County-level harvest numbers for other years between 1961 and 2007 were derived from a combination of sources: Montana Department of Natural Resources and Conservation (DNRC) cut-by-county reports for private lands, DNRC harvests for state lands, and USFS Cut & Sold Reports for the Bitterroot National Forest. Earlier removals (1945-1960) were estimated using available state-level harvest information. Since the distribution of harvest among ownership groups was known in both state and county datasets, it was possible to:

1. Use the 1961-1969 county-level data to establish the relative importance of each ownership group in the county-level cut (federal Bitterroot National Forest 95.4%; private forest 2.6%; other, mostly state, forest 2%)
2. Come up with an ownership-weighted estimate of 1945-1960 Ravalli County harvest as a function of the state-level harvest for those years.

Annual harvest numbers were converted to cubic feet (cf) from board feet (bf) TPO data (total bf / total cf) from different dates (see Spoelma et al., 2008). The conversion for 2004-2007 (3.69 bf/cf) was taken from the 2004 survey, while the 1998-2003 conversion (3.71) was taken from the 1998 survey, 1993-1997 used the 1993 conversion (4.79), 1988-1992 used the 1988 conversion (4.93), and dates prior to 1988 used an arbitrarily selected conversion of 5.0 bf/cf. It is likely that declining log sizes have led to a declining ratio of board-foot volume to cubic-foot volume. This relationship must be accounted for in the inference of cubic harvest volume from county-level board foot harvest records. Calculated cubic volumes were converted to units of carbon (first to pounds, then to metric tonnes, or megagrams) using the "Northern Rocky Mountains" factor published in Table 5.1 of Skog and Nicholson (2000). The resulting product carbon mass for each year (1945-2007, see Figure 1) was the input for subsequent inquiry into product disposition.

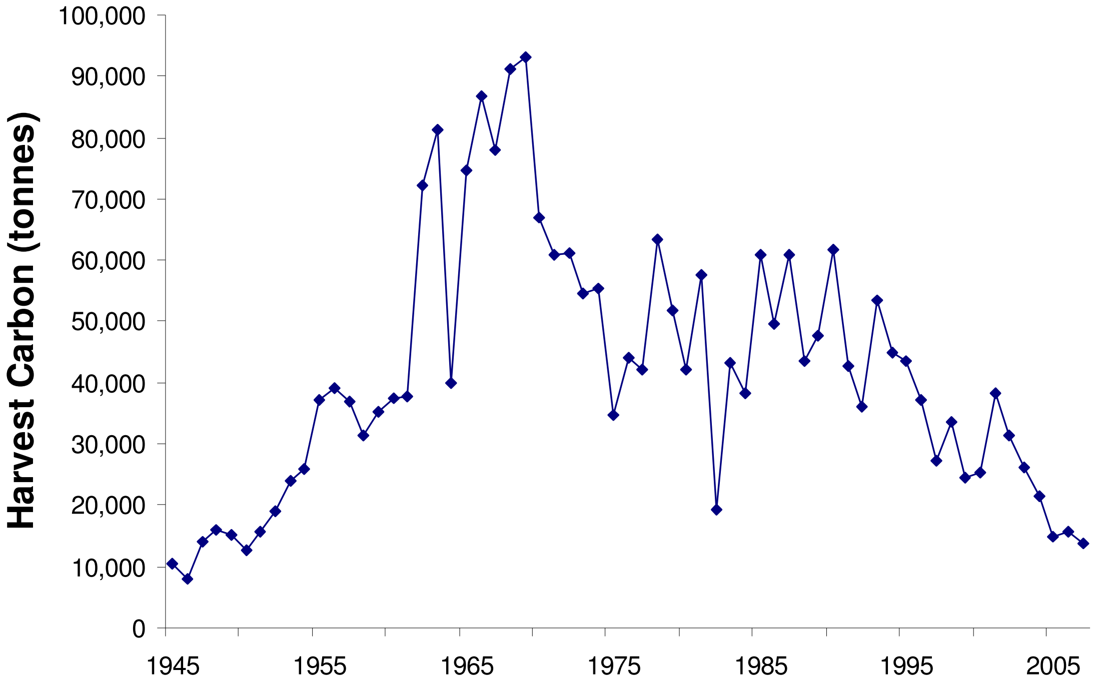

Figure 1: Harvest products from Ravalli County, MT, 1945-2007. Mass of carbon comes from administrative harvest volume records, transformed from board feet to cubic feet using TPO survey data and further translated to carbon using conversion factors in Skog and Nicholson (2000).

Estimating Emissions from Decomposition of Harvest Products

In general, assumptions regarding forest product longevity were taken from Table 6 in Smith et al. (2006), which shows changing fractions of the carbon in industrial roundwood among 4 different pools: 1) in use, 2) in landfills, 3) emitted with energy re-capture, and 4) emitted without energy capture. This table (partially illustrated here in Table 1) was based upon: national and regional assessments of wood harvest and end uses (partially summarized by Birdsey, 1996; Smith et al., 2004); basic assumptions about recycling rates and efficiencies (Skog and Nicholson, 1998), and studies of carbon decay limits and decay rates (Freed and Minz 2003, de Silva Alves et al. 2000). The disposition of the roundwood harvest volume from Ravalli County for each year from 1945 to 2007 was tracked over time using this table with the goal of monitoring all product carbon emissions for each year from 1985 to 2007. This study period corresponds with the Landsat TM era, and will complement satellite-derived information about growth and fire in future work.

While the dynamics of product life cycles have changed in the past and will continue to change in the future, generalized carbon flow heuristics may be applied over time with attention to major shifts in use or storage (Miner, 2006). In this study, the only implemented deviation from the dynamics discussed by Smith et al. (2006) was separate treatment of forest products discarded prior to 1980. Legislation in the 1970s mandated that dumps, which until then had been the primary means of waste disposal, be phased out by 1986 (Skog and Nicholson, 2000). Since landfills contain only a limited amount of oxygen, and therefore facilitate much less aerobic decomposition than dumps, the shift from dump- to landfill-disposal was consequential with regard to post-disposal emission rates. For the sake of simplicity, the move to landfill disposal was represented in this study as a discrete event in 1980. While the tables in Smith et al. (2006) show relatively slow emission rates consistent with the anaerobic conditions in most landfills, Skog and Nicholson (2000) estimated that 65% of the material sent to dumps was burned and/or emitted relatively quickly, with the remaining material decomposing over a 96-year cycle.

The amount of carbon entering the product pools in each year from 1945 to 2007 was tracked independently, and emissions from each of these "origin" years were calculated and summed for each year of the study period (1985-2007). For material harvested and processed after the shift in 1980 to the landfill dynamics addressed in the Smith et al. tables, calculation of carbon emitted each year was simply derived from the by-year change in the "emitted without energy" column (see Table 1) from one "year after production" to the next. Linear interpolation was used in this table to fill in values not supplied by Smith et al. Consider as an example the determination of how much carbon was emitted in 1989 from material harvested in 1982. If the roundwood harvested in 1982 (Year 0) was 10000 tonnes, and Table 1 indicates a fractional increase from 12.2% to 12.7% in carbon emitted without energy capture from Year 6 to Year 7, the calculated emission for 1989 from 1982 products will be 50 tonnes (0.5% of 10000).

For products produced and disposed of prior to the 1980-shift to landfills (i.e. 1945-1979), the dump dynamics outlined by Skog and Nicholson (2000) were implemented; 65% of disposed material was supposed emitted within the first year, with the remainder emitted uniformly over a 96-year period. Table 1 was used to determine the rate at which product carbon reached the dump; the disposal rate was assumed to be equal to the fraction of product carbon falling out of the "in use" category minus the fraction "emitted with energy re-capture." This year-by-year fraction of disposed carbon (*D* below) was used to track the arrival of part of each year's product cohort at the dump in each successive year. Further, emissions of dump contents were calculated for each year *A* as follows:

$$\sum_{o} TDC \qquad \text{(Equation 1)}$$

where *O* is each product origin year between 1945 and Year *A*, *T* is the mass in metric tonnes of carbon in the roundwood originally processed in year *O*, *D* is the fraction of *T* expected to reach the dump in Year *A* based upon Table 1. *C* is a constant:

$$C = RF \qquad \text{(Equation 2)}$$

where *R* is percentage of *TD* remaining following the initial burning at the dump (0.35 here), and *F* is the fraction of the assumed life cycle represented by Year *A* (1/96 here). Since the amount of carbon in dumps has been capped since 1980, and since that carbon is assumed to be emitted evenly on a 96-year cycle, emissions from dumped 1945-1979 products will be a constant until the first cohort of dumped products is envisioned to be completely emitted (i.e. 2041).

Many pre-1980 products were in use following 1980, of course, and their disposal must be accounted for via the landfill dynamics represented in Table 1. The percentage of products in use in 1980 from each harvest year since 1945 was determined using the "in use" column of Table 1. These products were assumed to be emitted using a rate of 0.17% per year. This rate, while somewhat arbitrary, is the 100-year average rate of emission without energy re-capture from Table 1 if the most volatile first year is excluded. First-year emissions were not considered in this emission rate because fact none of the emissions in this category (produced prior to 1980, disposed and emitted following 1980) could have occurred in the first year following harvest.

In summary, a fraction of each year's harvest products was estimated to be emitted in each subsequent year using product life cycle heuristics found in Table 1 and in the work of Skog and Nicholson (2000). Emissions from dumps and landfills from each product cohort were summed for each year to produce an estimate of overall emission of carbon resulting from forest products dating back to 1945. These emissions were plotted over time for the study period 1985-2007.

Results

As discussed above, county-level harvest volumes were tracked through the product cycle to disposal and eventual emission using three different scenarios: 1) landfill dynamics (see Table 1) for all harvests after 1979; 2) dump disposal (after Skog and Nicholson, 2000) for products discarded prior to 1980; and 3) landfill dynamics for products produced prior to 1980 but discarded thereafter. Table 2 shows part of the accounting (1961-1979) of the rate at which each year's forest products reached the dump; quantities in tonnes of carbon have been reduced by 65% to account for initial rates of burning (Skog and Nicholson, 2000). Similar accounting was done for estimated forest product levels from 1945 to 1960 (not shown). The total mass of carbon in dumps resulting from 1945-1979 forest products is estimated to be 148,288 tonnes, resulting in an annual emission of 1545 tonnes. Since the quantity of carbon in dumps has been capped since 1980 and emissions are distributed evenly over a 96-year period, calculated dump emissions will stay at this level until 2041. Emissions from older forest products still in use in 1980 (and thus assumed to have gone through landfills) was estimated to be 1101 tonnes per year.

Emissions from products estimated to have been discarded after 1980 were determined through the "emissions without energy re-capture" column in Table 1. Figure 2 shows the composite emissions from dumps and landfills. Total emissions declined throughout the study period from above 12000 tonnes per year to less than 9000 tonnes per year. The decline in emission in Figure 2 is not as pronounced as the decline in harvest volumes seen in Figure 1 because the amount of carbon accumulated in landfills since 1980 has

Table 2: Rate of Deposition into Current Dump Storage.

		Year Sent to the Dump																		
Year Produced	**Metric Tonnes C**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**
			------------------------------- Tonnes of carbon not initially burned and now decomposing on a 96-year cycle -------------------------------																	
1961	37741	1149	343	317	277	251	238	198	198	172	172	159	114	114	114	114	114	79	79	79
1962	72195		2198	657	606	531	480	455	379	379	328	328	303	217	217	217	217	217	152	152
1963	81156			2471	739	682	596	540	511	426	426	369	369	341	244	244	244	244	244	170
1964	39841				1213	363	335	293	265	251	209	209	181	181	167	120	120	120	120	120
1965	74749					2276	680	628	549	497	471	392	392	340	340	314	225	225	225	225
1966	86896						2646	791	730	639	578	547	456	456	395	395	365	262	262	262
1967	77920							2373	709	655	573	518	491	409	409	355	355	327	235	235
1968	91235								2778	830	766	671	607	575	479	479	415	415	383	275
1969	93162									2837	848	783	685	620	587	489	489	424	424	391
1970	67067										2042	610	563	493	446	423	352	352	305	305
1971	60752											1850	553	510	447	404	383	319	319	276
1972	61128												1861	556	513	449	407	385	321	321
1973	54447													1658	495	457	400	362	343	286
1974	55255														1683	503	464	406	367	348
1975	34621															1054	315	291	254	230
1976	44144																1344	402	371	324
1977	42090																	1282	383	354
1978	63412																		1931	577
1979	51685																			1574

been growing. Thus, emissions from products produced and discarded at the end of the study period are augmented by emissions from products originating earlier in the period. In general, annual variation in overall product carbon emission is most sensitive to recent harvesting trends (i.e. black bars in Figure 1) because: disposal rates are highest soon after harvest (Table 1), and because this accounting system treats emissions from pre-1980 products as a constant.

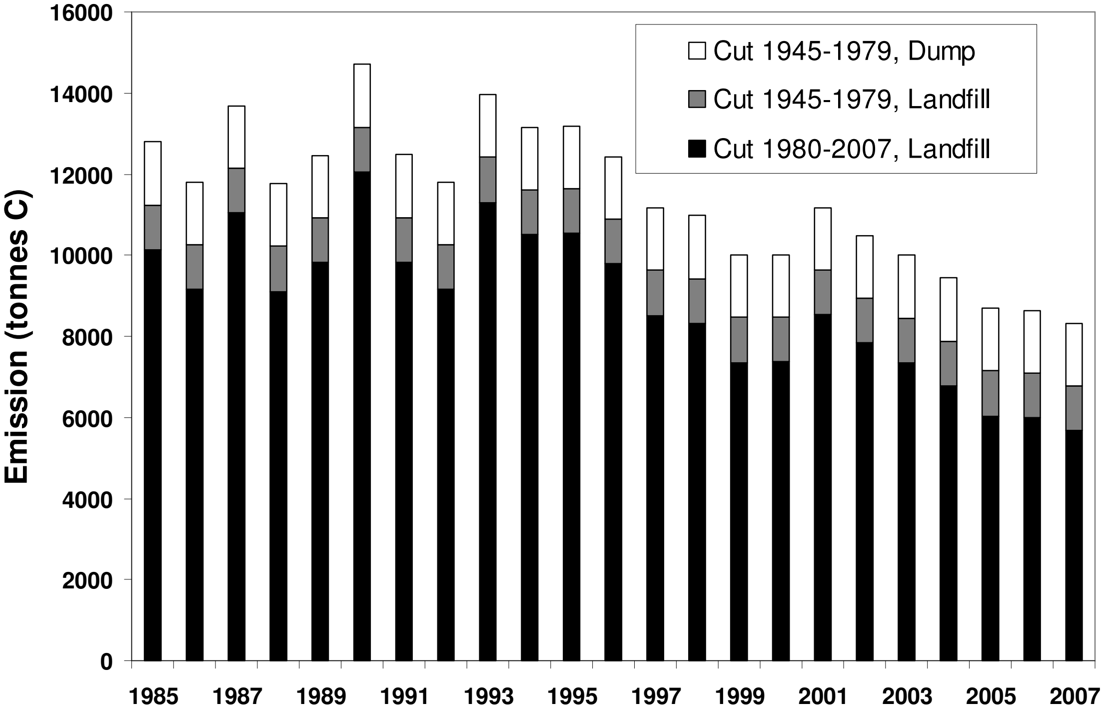

Figure 2: Annual product carbon emissions in Ravalli County, 1985-2007. Three product pathways were considered: produced after 1980 and sent to a landfill (black), produced 1945-1979 and sent to a landfill (gray), and produced 1945-1979 and sent to a dump (white).

Discussion

The legacy of carbon associated with historical forest products must be considered when assessing the role management plays in forest carbon cycles. Because the forest product cycle of processing, use and disposal can defer release of carbon into the atmosphere, harvest can be seen as a relatively benign form of disturbance. Deferral of product emissions is not permanent, however, and accurate comparison of the effects of harvest vs. fire and other factors, as is the goal of currently ongoing research, depends upon adequate estimates of current emissions from products manufactured over preceding decades.

Remote sensing using historical Landsat imagery, as calibrated with inventory data, can provide temporally and spatially consistent harvest information (Healey et al., 2007). Indeed, in countries where there is no systematic monitoring of forest industry output, remotely-sensed estimates of volume removal could form the basis of historical product assessments. In the United States, however, the most credible county-level estimates of harvest trends come from administrative records related to taxes and TPO industry surveys. Mill-based survey assessments are presumed to have little error, and are available across much of the country for the last 50 years (Smith et al., 2004). The long continuous county-level time series used here may not be available in some parts of the country where the timber industry is less important than in western Montana, but in these cases, TPO surveys (typically produced once every 5 or so years) might be extrapolated to fill in the time series.

While the use of TPO data obviates modeling error that would be present if harvest numbers were provided by remote sensing, two potential sources of error should be emphasized in the historical product carbon accounting approach described here. One source of uncertainty may be potential mismatch between the regional spatial scale of the reference data used in Smith et al.'s product dynamic tables (see Table 1), and the relatively small portion of the Rocky Mountain region studied here. Specifically, the species composition of Ravalli County's forests and the mix of its product types may deviate from regional averages. Secondly, while the disposition rates in Table 1 may accurately portray current product life cycles, application of those rates to historical harvests may mask important changes in the rate that product carbon is emitted. The system discussed here accounts for a shift in destination from dumps to landfills, for example, but it does not address potentially important changes in recycling rates (Skog and Nicholson, 2000).

The emissions described in this paper do not distinguish between carbon dioxide and methane. Since the global warming potential of methane (over a 100-year period) is estimated to be 21 times that of carbon dioxide (IPCC, 1996), the effective of Ravalli County's product carbon emissions would actually be higher if methane contributions were translated into carbon dioxide equivalents. However, rate of capture of landfill methane has increased recently and is currently about 50% (Skog, 2008). So, the effect of methane on emissions in terms of carbon dioxide equivalents would be to raise the estimates given here, but in a way that continues to decline as more methane is captured.

Nevertheless, the processes used to create the historical emission estimates in Figure 2 are straightforward and could easily be modified to accommodate life cycle heuristics that are better adapted either spatially or temporally to the unit of analysis. Resulting county-level product emission estimates will be compatible in spatial and temporal scale with estimates of carbon flux related to other processes like growth and fire. Synthesis of different carbon cycle components and analysis of their behavior in relation to forest management should yield fundamental ecosystem-specific information about the relationship between management and landscape-level carbon movement.

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