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Report to the Oregon Greenhouse Gas Commission

Modeled Carbon Stores in Oregon's Wood Products: 1900-2016

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Abstract

A process-based model was used to estimate the accumulation of solid wood products, both those being used and disposed, resulting from timber harvest in Oregon between 1900 and 2016. The model tracks the flows of harvest-related carbon into the wood products system, among pools within this system, and those back to the atmosphere. The model was parameterized to the extent possible using results from surveys of Oregon's manufacturing industry as well as general knowledge about how the manufacturing and disposal systems have changed over time. The simulations indicate a total of 1067 Tg C (Teragrams=million metric tons) have been harvested and 247 Tg C of solid product-related carbon has accumulated over the 1900 to 2016 period. The largest store is in long-term structures such as buildings, but currently the fastest growing store is in landfills. Different trends in harvest among general ownerships have resulted in different patterns of accumulation; and although there has been a general pattern of accumulation for all ownerships, the post-1990 decline in harvests from federal lands have caused stores related to that ownership to recently decline. The overall rate solid stores are changing relative to the harvest for the 2003-2013 period is 13.9%. This means that 13.9% of the harvest in this period is equivalent to the net accumulation of stores in these pools. Thus, although harvests are increasing stores in these pools, a large share of the harvest is either being emitted or offsetting losses from stores resulting from previous harvests. There is considerable variation in this metric by general ownerships, with the lowest value for harvests related to federal lands (-66% indicating more is being lost than harvests can replace) and the highest for lands other than federal or private (32%). For private lands the analysis indicates that 22% of the harvest is equivalent to the net increase in stores related to this ownership. A sensitivity analysis indicates that the lifespan of long-term structures and carbon in landfills has an effect on the estimates, but varying the values over a 4-fold range does not change the sign or the order of magnitude of the net increase in stores relative to harvests.

Introduction

Store in harvest-related carbon and the changes in these pools over time cannot be inventoried. It must be modeled. The most rigorous method to model these pools involves a process-based model. The following report describes one such process model and the results from simulations using Oregon-based data. In addition to modeling values for the entire state, harvests and the stores resulting from these harvests are divided into general forest ownerships (i.e., federal, private, and other).

The analysis considers harvests between 1900 and 2016 to estimate the net change in harvest-related stores for the last decade. While earlier harvests may not seem relevant to what is going on most recently, they are highly relevant. This is because the current net change in these stores depends not only on the recent harvest, but also on the accumulation of all the harvest-related carbon in previous years. Given the potentially long life-span of some forms of harvested carbon (buildings and landfills), what is happening today can depend on what happened over 100 years ago. The same is also true for carbon stored in the forest ecosystem—changes we observed today are in part a response to what happened to forests decades and in some cases centuries ago.

The ultimate goal of this analysis is to provide a relative index of the net accumulation of carbon in solid forms that has resulted from harvest. Solid forms of carbon include mulch, paper, and wooden structures such as buildings. The net accumulation depends not only on the amount flowing into this part of the forest carbon system, but also the amount that is lost either in manufacturing, use, or disposal of harvested carbon.

Methods

Model overview

The model used was adapted from Harmon et al. (1996). A detailed description can be found in that article. In very general terms the model tracks the flows of harvested stem carbon into different manufacturing streams, the flows into different uses, and flows into different forms of disposal (including recycling) as well as the flows to the atmosphere via decomposition and combustion (Figure 1).

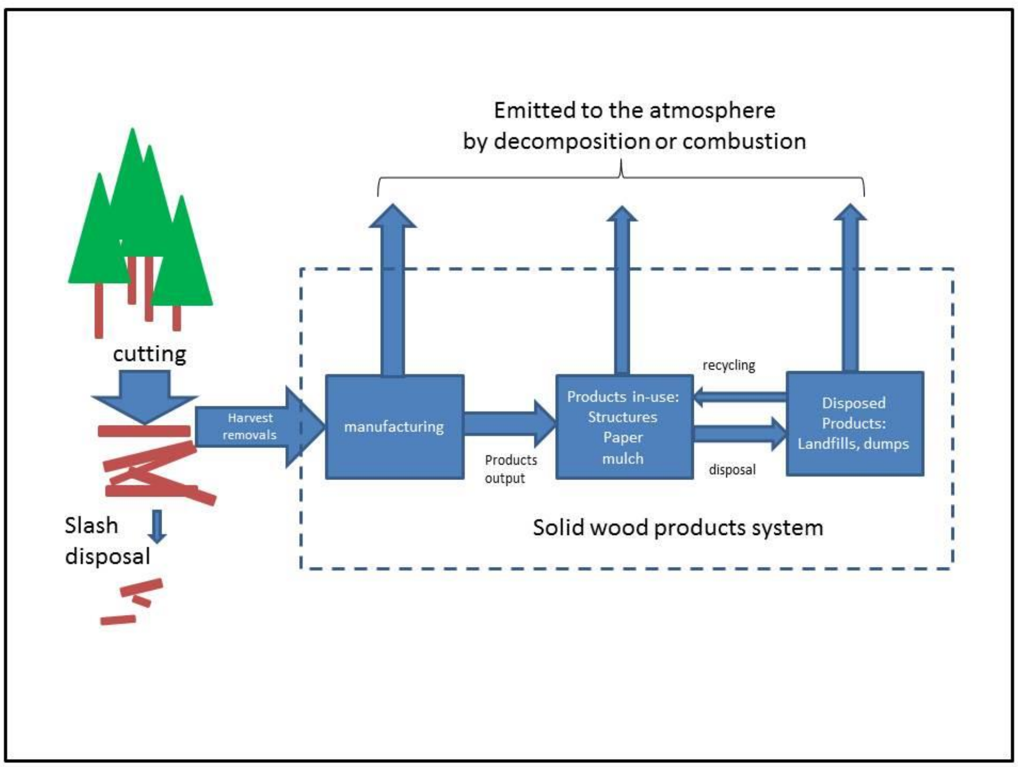

Figure 1. Flows of carbon into and out of the solid wood products portion of the forest sector. Trees are cut during harvest, but only a fraction is removed forming the input to the solid wood products system. Some carbon is lost to the atmosphere during manufacturing; some is turned into products that are

stored when being used and after they are disposed. During both use and after disposal carbon is lost or emitted to the atmosphere.

The generic description of all the flows leaving a pool is:

Out $=k * \text{Pool}_{t-1}$

Where Out is the flow out of the pool, *k* is a proportion of the pool going out, and is the size of the pool the previous time step. This relationship creates a negative feedback that is the key to understanding how these pools accumulate carbon over time.

To calculate the net change in the store (NCS) one subtracts the output from the input:

NCS= Input-Output

To calculate the store in year t, one adds the store from the previous year t-1 to the NCS:

$\text{Pool}_t = \text{Pool}_{t-1} + \text{NCS}$

These calculations are used throughout the model. In the case of manufacturing related pools, it is assumed that 100% of the pools are sent to the various outflows, hence there is no accumulation in these pools. In the case of products in-use or those that have been disposed there is an accumulation in the pool because the proportion leaving the pool is less than 100%. The losses from the latter pools therefore depend on the previous accumulation in the pools, some of which could be accumulating carbon for centuries.

A synopsis of the calculations for each part of the model follows.

Manufacturing. The first step in manufacturing is to divide harvested stem carbon into bark and wood. It was assumed that stems were comprised of 12% bark and 88% wood. The flow of bark and wood was determined by multiplying these proportions by the total stem harvest. The wood flow is then divided into pulp, saw, and veneer logs. Minor uses for poles, etc were included in saw logs. Bark flow was divided into production of mulch, waste to be incinerated or used to generate energy, or chips. Mulch production was used as the input to mulch stores, chips as an input to paper manufacturing, and waste to the atmosphere (since it is combusted and that goes into the atmosphere whether or not energy is recovered). Saw log manufacturing produced lumber, chips, and material that were combusted either to reduce volume or produce energy. As with bark the latter use of waste was considered an emission to the atmosphere because it involved combustion. Veneer log manufacturing produced plywood, chips, and material that were combusted either to reduce volume or produce energy. As with bark and saw logs the latter flow was considered an emission to the atmosphere because it involved combustion. Paper manufacturing received inputs from pulp logs and well as chips from bark, saw log, and veneer manufacturing. These inputs are divided into a flow of paper produced versus losses in the manufacturing process due to decomposition and combustion. All these flows were calculated by multiplying the input into these manufacturing streams by the proportion going in to each output stream. As noted above the inputs to these pools equal the outputs because 100% of the input is accounted for in the output streams.

Products in Use. Four products are tracked in-use: mulch, paper, short-term structures, and long-term structures. Each of these pools has an input and each have output flows that account for losses via decomposition and combustion as well as those related to disposal. The input to mulch comes from the bark manufacturing flow streams and the output is assumed to be from decomposition. It assumed that mulch would have an average life-span of 10 years or a maximum life-span of 46 years. Paper in-use received inputs from paper manufacturing and had two loss flows: decomposition and disposal. The decomposition rate was set to give paper an average life-span of 7 years, implying a maximum life-span of 30 years. Disposal was set at a similar value. Combined these two flows gave paper in-use an average life-span of 3 years and a maximum life-span of 15 years. Short-term and long-term structures both had inputs from the saw and veneer log manufacturing flows (lumber and plywood, respectively). Losses from these pools were in the form of disposal as well as decomposition and combustion occurring during use. Disposal and decomposition/combustion losses for short-term structures were set to give an average life-span of 7 years or a maximum life-span of 31 years. Disposal rates were assumed to comprise two-thirds of the total flows. For long-term structures the flows from disposal and decomposition/combustion were assumed to be equal and set so that the average life-span of this carbon was 50 years, implying a maximum life-span of 230 years.

Disposed products. Paper, short-term, and long-term products that were disposed were divided into four different streams: incineration, recycling, open dumps, and landfills. The flow going into incineration was assumed to go into the atmosphere given that this involves combustion. The proportion recycled was used to adjust the net disposal rate. For example, if half the disposed paper is recycled, the net disposal rate would be halved relative to the case in which there is no recycling. The disposed paper and wood not being incinerated or recycled was sent to either open dumps or landfills. Both these pools have losses associated with either combustion or decomposition. Materials flowing into open dumps were assumed to have an average life-span of 3 years or a maximum life-span of 14 years. That flowing into landfills was assumed to have an average life-span of 200 years or a maximum life-span of 920 years.

Data Sources

The data used in these calculations were taken from Harmon et al (1996) and updated using USFS reports on the forest products industry and harvest to fill in values for the post 1992 period (Ward 1997, Brandt et al 2003, Gale et al 2012, and Simmonds et al. 2016). The parameters taken from these reports included the allocation of harvested stems, the production of different products from the saw and veneer log manufacturing streams, and the proportional share of harvests by ownership. For all the parameters except the latter the calculations were based on cubic volume and not board feet. Shrinkage as not considered a loss, as it changes the volume, but not mass of the lumber or plywood. Harvests after 1942 from different ownerships was based on ODF reports. Prior to 1942 it was assumed that federal harvests gradually increased from zero in 1900 to the 1942 value. Further it was assumed that private harvested comprised 95% of the non-federal harvests during this time. This based on the 1942 to 1952 proportion of harvests in private versus non-federal harvests.

Results

Harvest Patterns

The amount of stem C harvested was highest in the 1950 to 1980 period (Figure 2). Prior to 1950 the harvest generally increased, although there were declines associated with the Great Depression and other economic downturns. After 1980 the largest decline occurred due to a reduction in harvesting on Federal forest lands. Temporary declines with the recessions in the early 1980's and 2008 are also evident.

The share of harvest among the general ownerships has changed markedly over the 1900 to 2016 period. Initially the harvest was primarily on private forest land, but between 1950 to 1980 Federal forest land provided the largest share of the harvest (approximately 52%). Since 1990 private ownerships have provided 75 to 83% of the harvest. Other ownerships, including state and tribal lands, have always been a minor share of harvests, but the proportion from those lands has steadily increased over time.

The majority of stem material harvested has been wood (Figure 3). The cumulative harvest of stems over the 1900 to 2016 period was estimated as 1067 Tg C. This was divided into 939 Tg C of wood and 128 Tg C of bark.

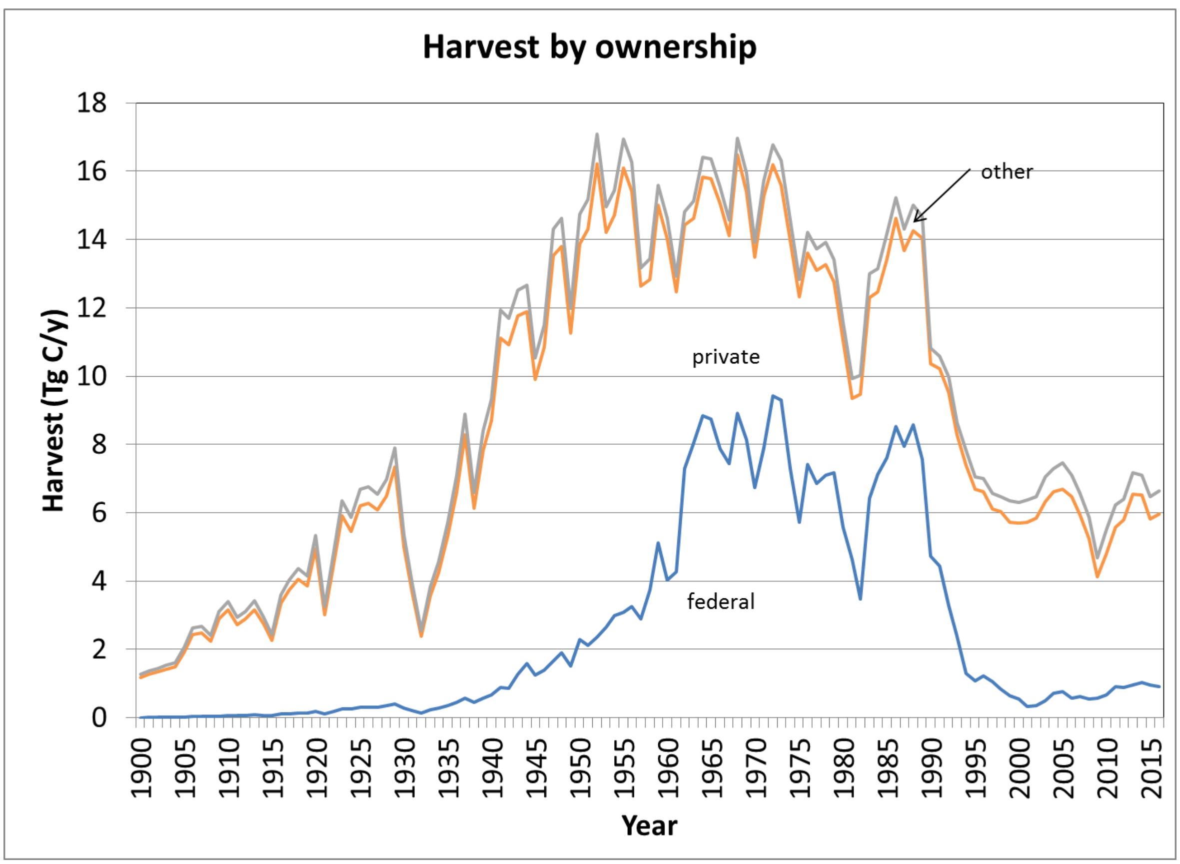

Figure 2. Forest carbon harvest in stems by ownership from 1900 to 2016.

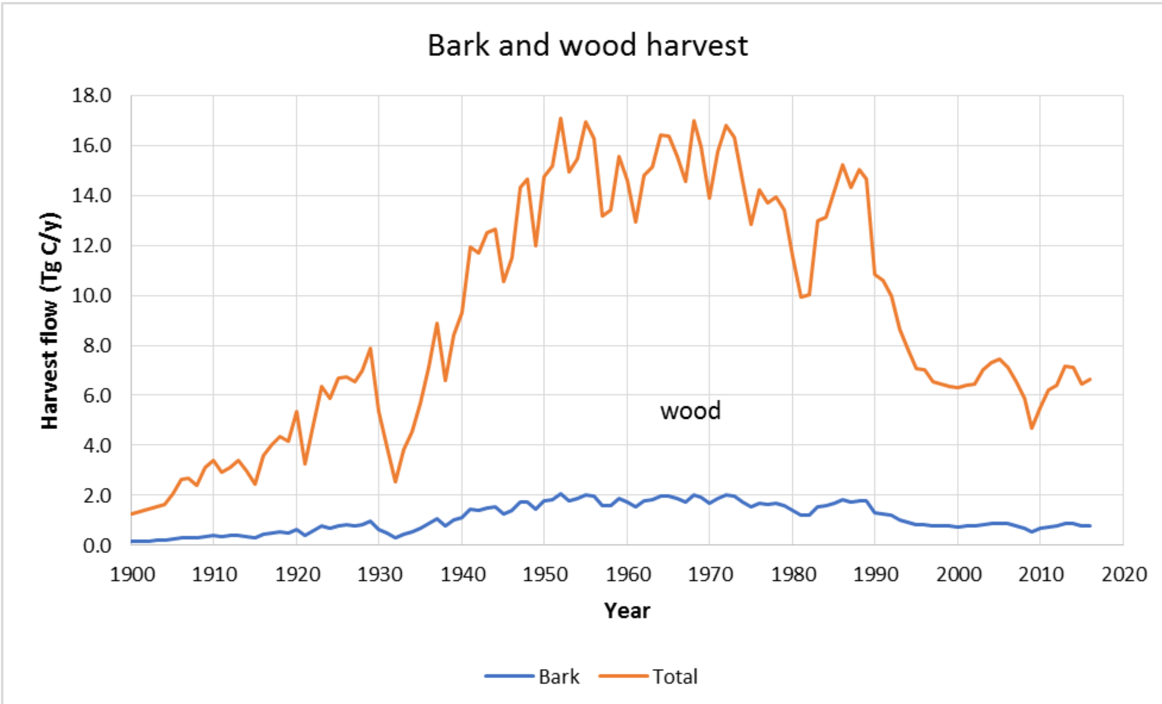

Figure 3. Harvest of stem wood and bark for all ownerships from 1900 to 2016.

Allocation of Harvested Stems

Saw logs have been the primary manufacturing stream that harvested wood has been allocated toward; with the lowest share being 57% (Figure 4). Veneer logs were the second largest manufacturing stream reaching its highest point in the 1960's of around 37%. Pulp log allocation has been highly variable, but never has exceeded 16%.

The flows into different wood manufacturing streams are largely influenced by the temporal trends in harvest with some influence of changes in allocation patterns. Over the 1900 to 2016 period 673 Tg C of harvested wood has been allocated to saw logs (71.7%), 189.9 Tg C to veneer logs, (20.2%), and 76.3 Tg C to pulp logs (8.1%).

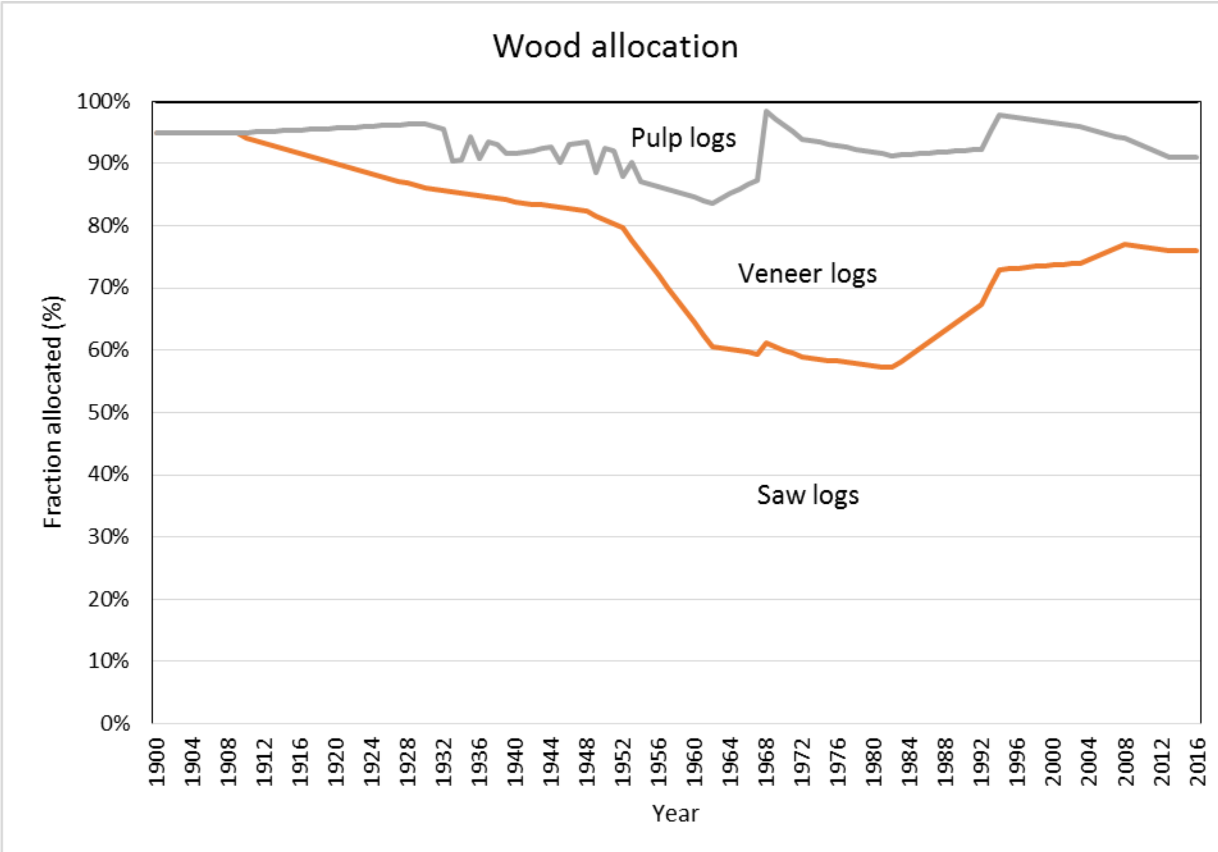

Figure 4. Proportional allocation of harvested stem wood 1900 to 2016.

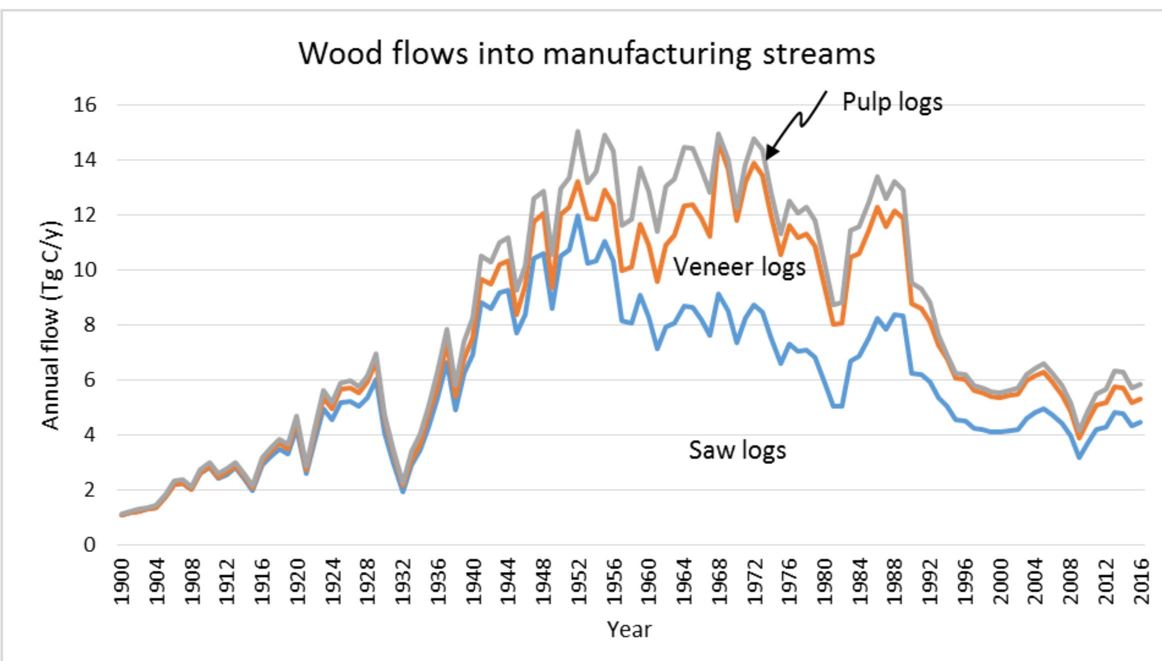

Figure 5. Flows of harvested wood into different manufacturing streams from 1900 to 2016.

Manufacturing

Manufacturing tracks how bark and wood was used as well as how chips, a by-product of manufacturing, were processed into paper.

The primary use of bark has been either as a waste to be incinerated (prior to 1970) or as a fuel source (after 1970) (Figure 6). A very minor use has been as chips. The other use has been as mulch. As with wood, the primary factor controlling the flow of bark into different uses has been variation in the stem harvest (Figure 7). Over the 1900 to 2016 period a total of 111.8 Tg C has been either been incinerated or used as fuel and 16 Tg C has been used as mulch. If one assumes that since 1975 all the latter flow has involved energy capture then a total of 38.6 Tg C might be offset to some degree by energy substitution. The degree this emission is countered by energy substitution would depend on the type of fossil fuel being replaced as well as the degree non-fossil energy is used.

Sawlog processing has largely resulted in lumber, however, the proportion of lumber produced has varied from 40% to 57% (Figure 8). The declines in the 1920 to 1950 period were associated with additional processing steps (e.g., rough lumber was planed), whereas the gains since 1950 have been associated with technological improvements geared toward increasing efficiency. As with bark, prior to 1970 the "waste" was incinerated, whereas after that point it was used to generate energy as hogg fuel. Another use of this "waste" was as chips for paper manufacturing.

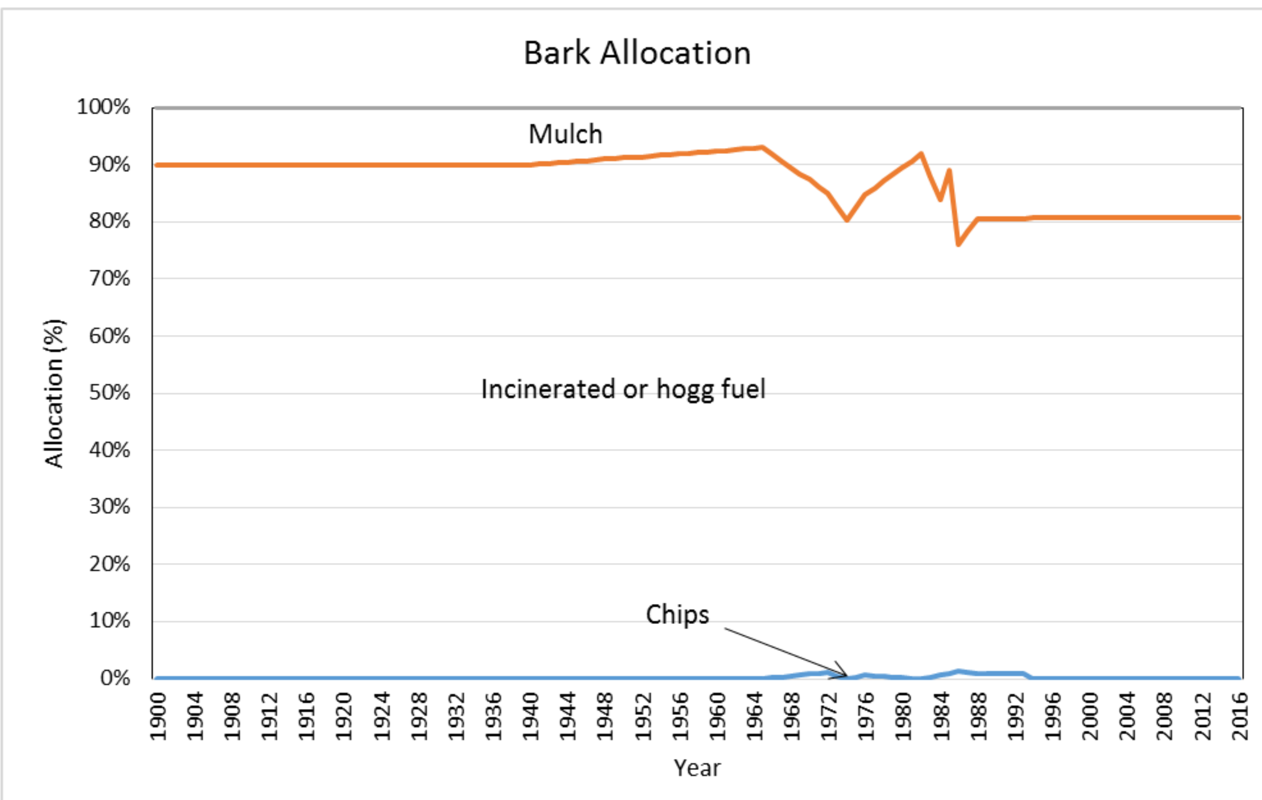

Figure 5. Proportional allocation of harvested stem bark into different uses 1900 to 2016.

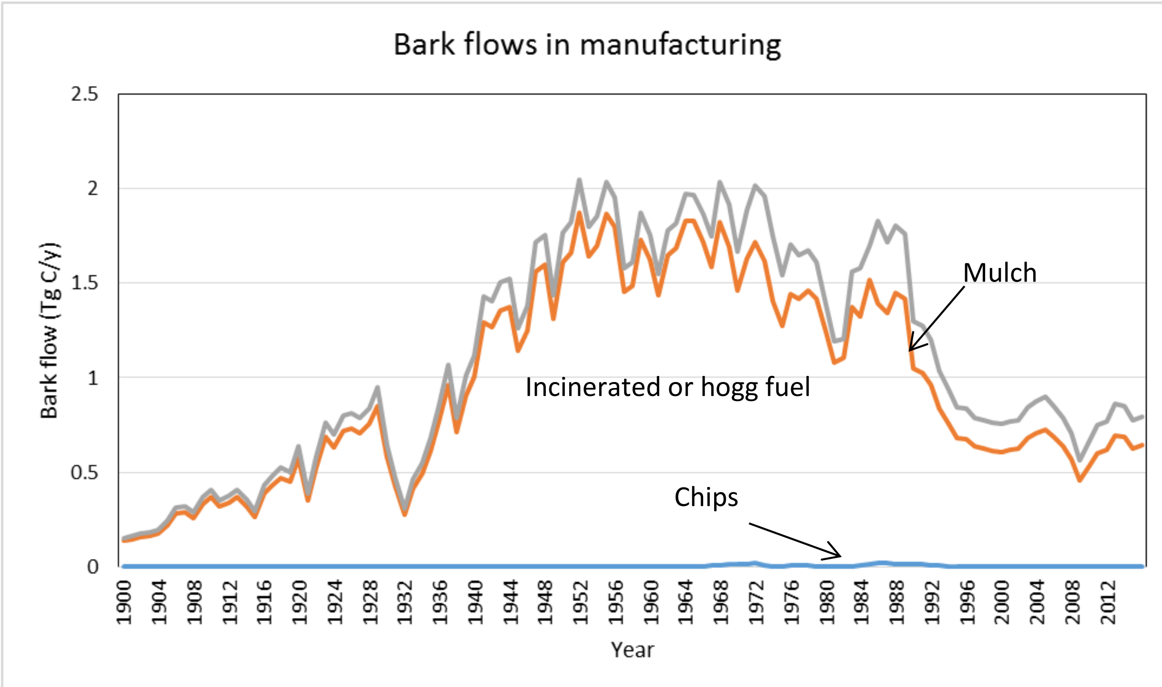

Figure 7. Flow of bark into different use streams 1900 to 2016.

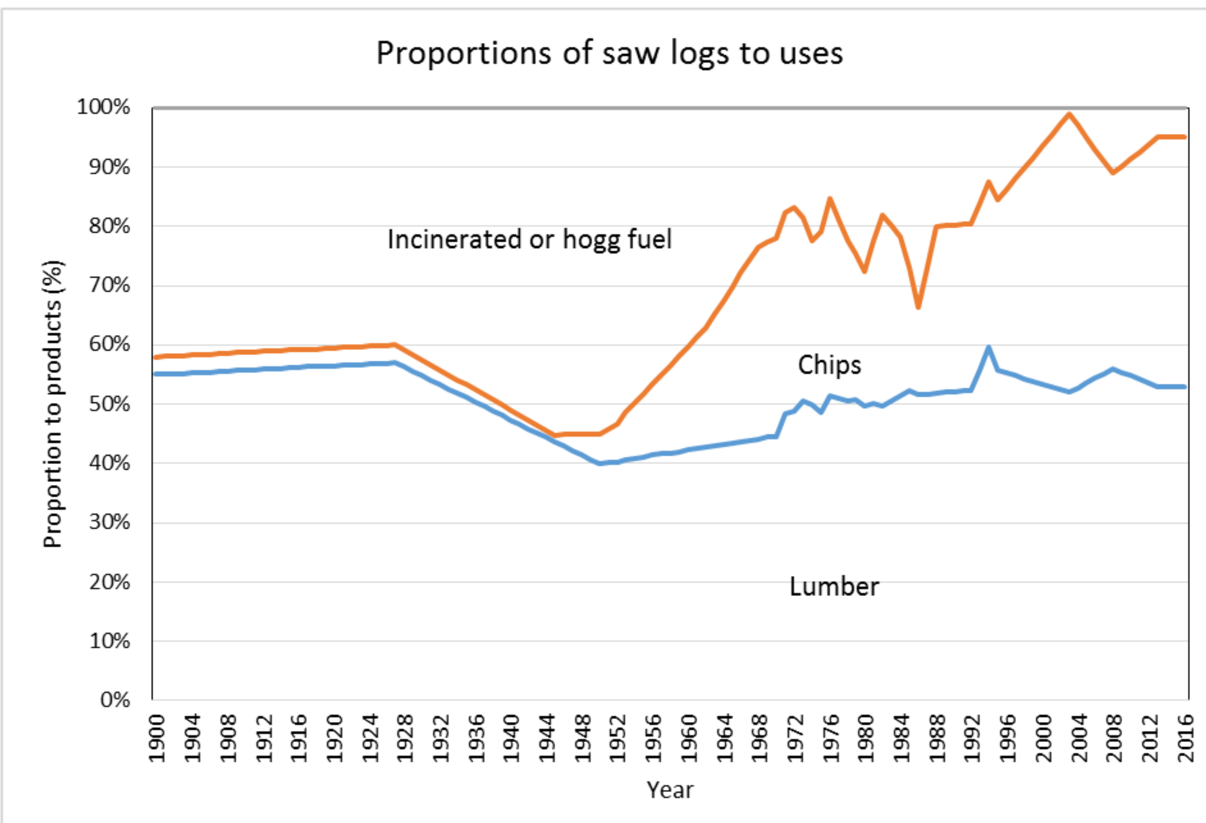

Figure 8. Proportional allocation of saw logs into different uses 1900 to 2016.

In terms of carbon flows, the amount of harvest as well as the changes in use has both influenced the amount of carbon being produced as lumber (Figure 9). That is before 1940 the increase in stem harvest leads to an increase in lumber flows, but after that time technological improvements have maintained the flow lumber despite a decline in flows to saw logs. The major decline in the incinerated-hogg fuel flow is largely associated with a diversion into chips for paper production. The recent flow into this category appears to the lowest over the 1900 to 2016 period. Over the 1900 to 2016 period a total of 327.8 Tg C of lumber has been produced, 121.4 Tg C of chips, and 223.5 Tg C of waste that has been combusted with or without energy capture. If one assumes that since 1975 all the latter flow has involved energy capture then a total of 35.7 Tg C might be offset to some degree by energy substitution, but as with bark that depends on the energy that is being substituted for.

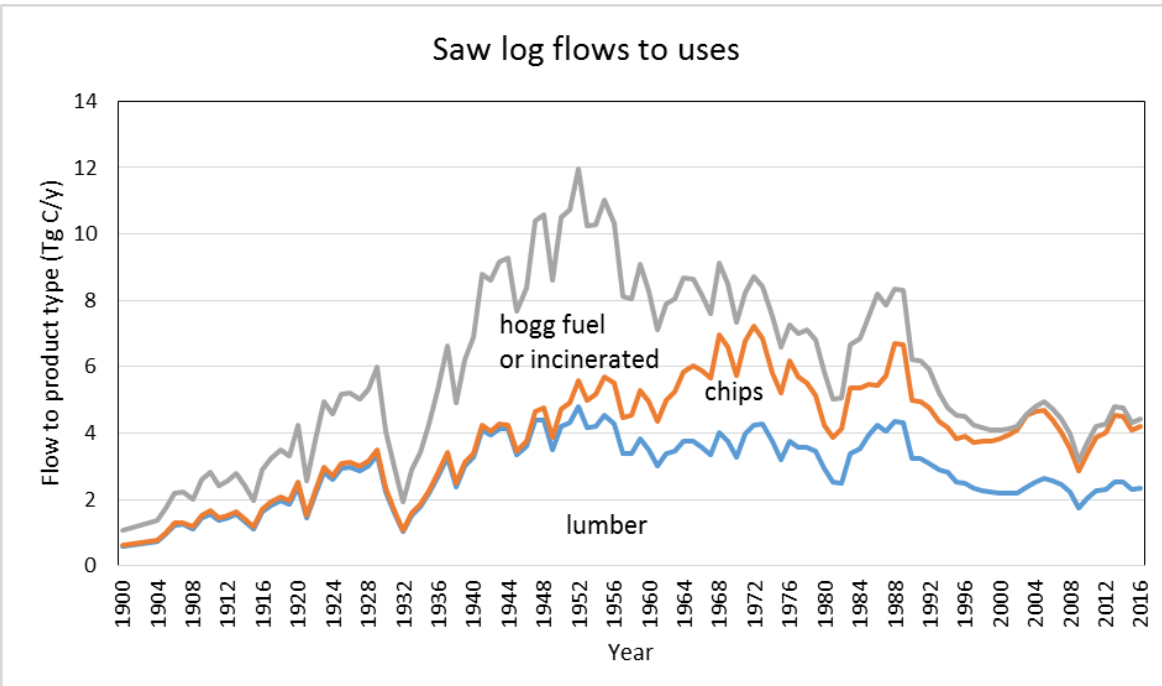

Figure 9. Flow of saw logs into different uses 1900 to 2016.

Veneer log processing has largely resulted in plywood, with the proportion of plywood produced has increasing steadily over the 1900 to 2016 period (Figure 10). The amount of veneer logs resulting in either incinerated waste or hogg fuel has steadily declined over time. As with bark, prior to 1970 the "waste" was incinerated, whereas after that point it was used to generate energy as hogg fuel. Another use of this "waste" was as chips for paper manufacturing.

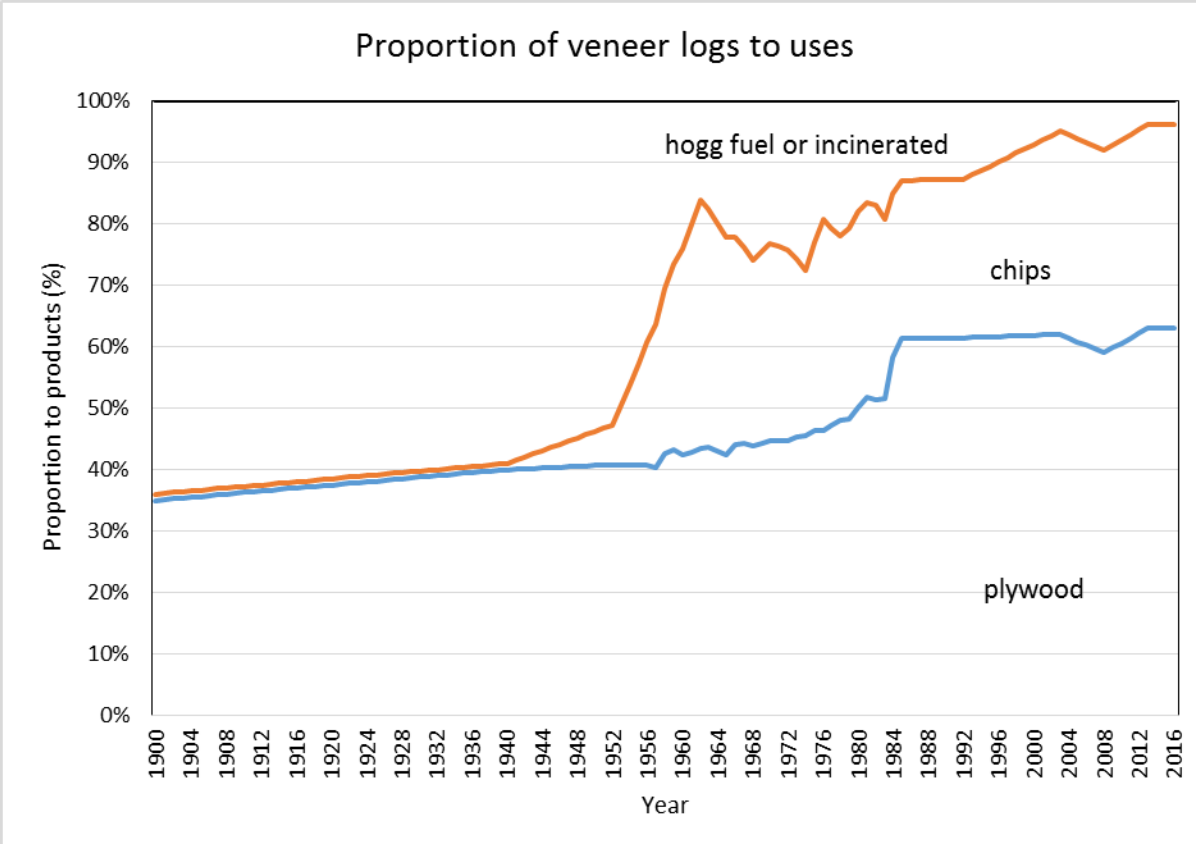

Figure 10. Proportional allocation of veneer logs into different uses 1900 to 2016.

In terms of carbon flows, the amount of harvest has influenced the amount of carbon being produced as plywood (Figure 11). The major decline in the incinerated-hogg fuel flow is largely associated with a diversion into chips for paper production. As with saw logs, the recent flow into this category appears to the lowest over the 1900 to 2016 period. Over the 1900 to 2016 period a total of 93.9 Tg C of plywood has been produced, 50.5 Tg C of chips, and 45.5 Tg C of waste that has been combusted with or without energy capture. If one assumes that since 1975 all the latter flow has involved energy capture then a total of 12.8 Tg C might be offset to some degree by energy substitution, the value being determined by the type of energy being replaced.

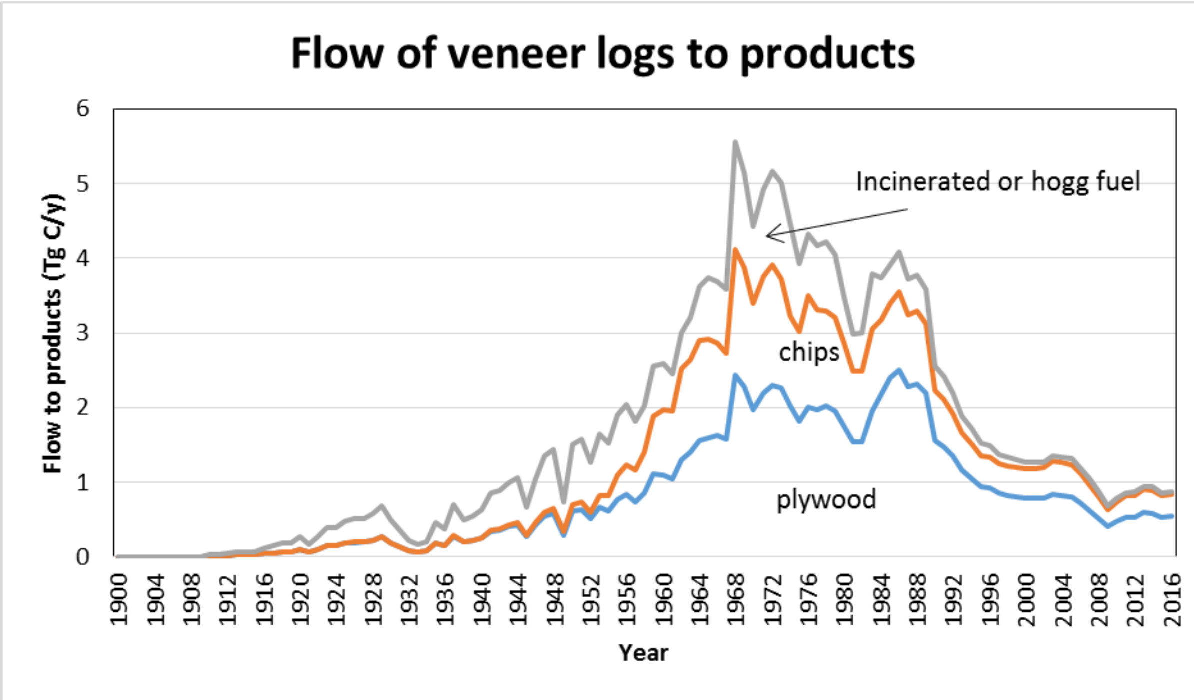

Figure 11. Flow of veneer logs into different uses 1900 to 2016.

The final manufacturing stream is paper production which accounts for the production of chips associated with bark use and saw log and veneer log manufacturing. Slightly over 50% of the chips entering paper manufacturing result in paper products (Figure 12). Over the 1900 to 2016 period a total of 248.6 Tg C of chips have been produced resulting in 128.6 Tg C of paper. If one assumes that half the paper manufacturing waste has been used for energy production and the other half has been decomposed in sludge pools, then potentially 60 Tg C have been associated with energy production. However, this is likely high and if only the post 1975 period is considered the value would be 29.3 Tg C.

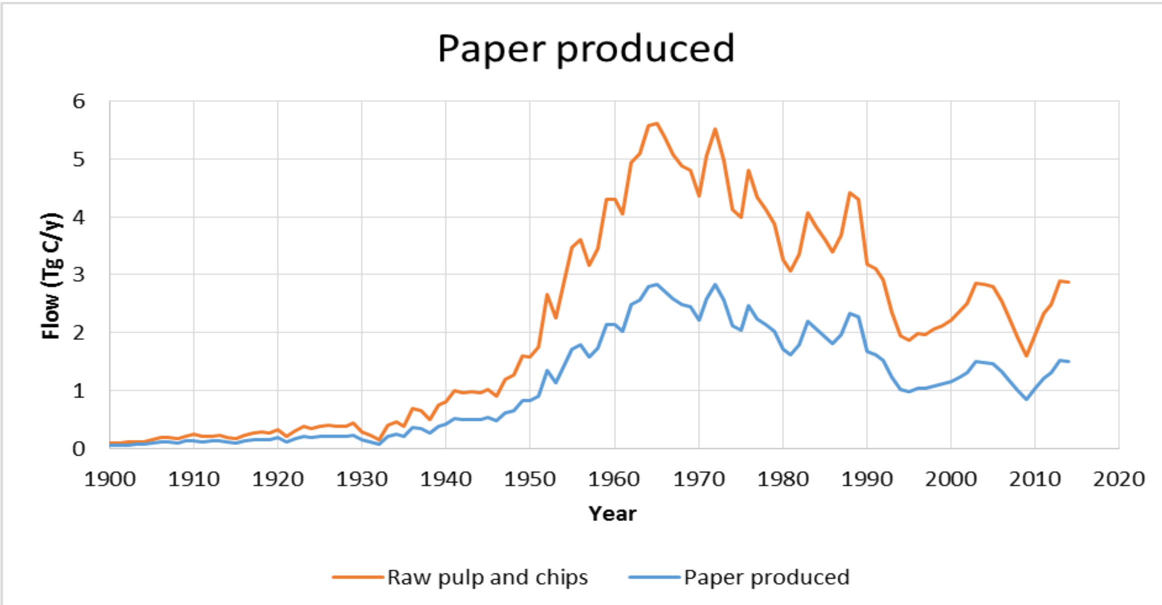

Figure 12. Flow of raw pulp and chips and paper produced over the 1900 to 2016 period.

Products in Use

Products in-use included mulch, paper, short-term structures, and long-term structures (e.g., buildings). For all ownerships combined solid products in use largely increased until 1990, but have declined slightly since that time (Figure 13a). Between 1900 and 2106 a total of 168.2 Tg C of solid wood products have accumulated. The majority (93.7%) of solid products stores have been in long-term structures, with the rest divided between mulch (0.9%), paper (3.3%), and short-term structures (2.1%).

Harvests on federal lands have resulted in a delayed accumulation of solid wood products (given harvests themselves did not start in large scale until the 1940's) (Figure 13b). Since 1990 there has been a large decline in solid products associated with federal harvests, largely due to the large decline in the harvest amount coming from these lands. Over the 1900 to 2016 period harvests on federal lands have resulted in a 52.2 Tg C of solid products accumulating. This represents approximately 31% of the total store in solid products.

Harvests on private lands have resulted in the majority (62%) of solid wood products carbon stores (Figure 13c). In contrast to harvests from federal lands, those from private lands have resulted in an increase in solid wood products stores except in periods of major economic downturns. The total amount accumulating over the 1900 to 2016 period from harvests on private lands was 104.2 Tg C. The accumulation curve suggests that the accumulation rate for private harvests is slowing down, largely due to the fact many of these stores have either reached or are approaching a quasi-steady-state.

Harvests from ownerships other than federal and private appear to have resulted in the steadiest increase in solid wood products harvests (Figure 13d), however, these harvests also represent the smallest share of the total (6.3% or 10.6 Tg C).

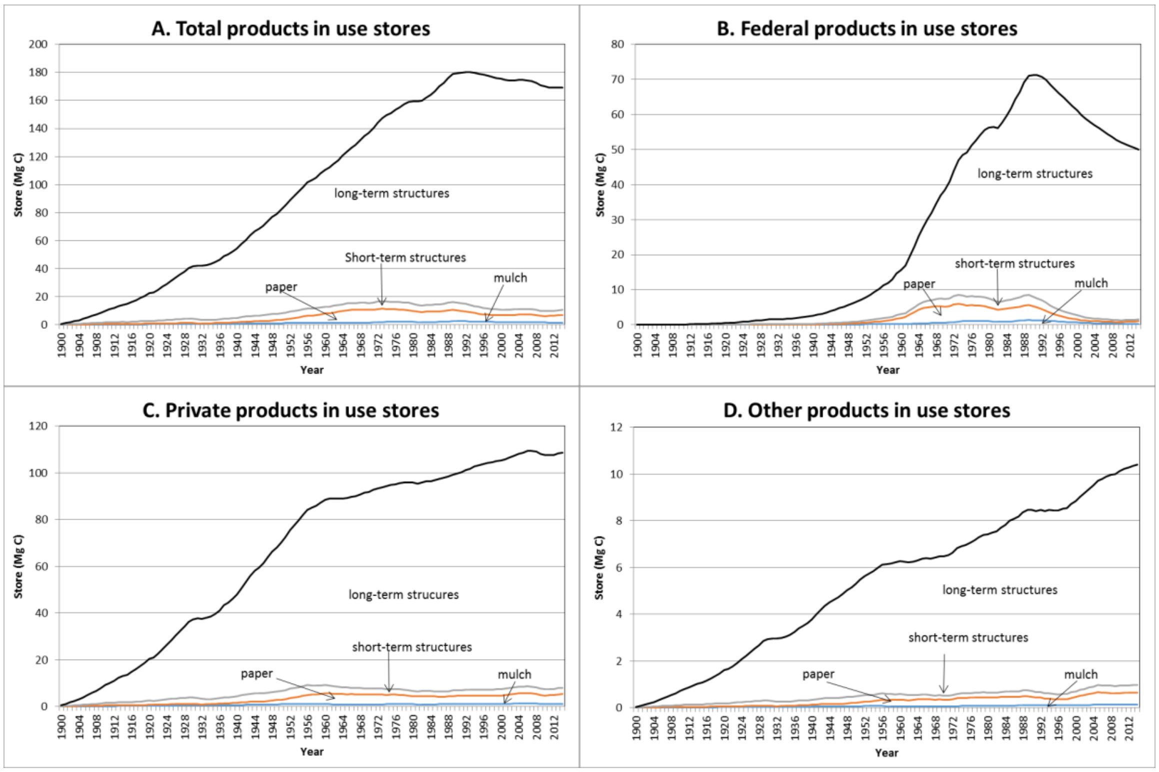

Figure 13. Store of solid wood products over the 1900 to 2016 period for different ownerships. These are cumulative plots, the lowest line represents the store in mulch, the next line the store in mulch plus paper, the next store in all but long-term structures and the upper line the total of all forms. Note that the stores axis differs for the different ownerships.

Disposed Products

The fate of disposed paper and wood products have varied over time with the main difference being the shift from open dumps to landfills and the increased amount of recycling (Figure 14). The latter effectively reduces the disposal flow into incineration, open dumps, or landfills. The flow to landfills greatly increased after the 1970's and since that time has exceeded 70% of the disposed solid products.

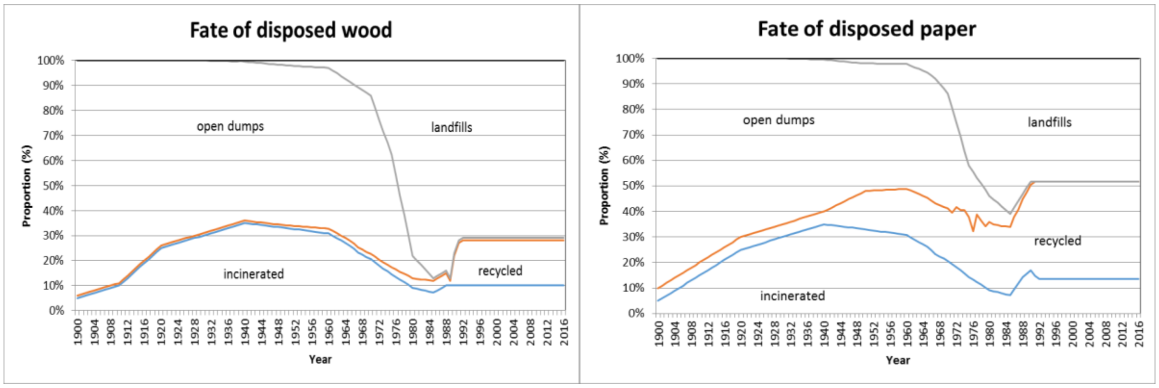

Figure 14. Fate of disposed paper and wood between 1900 to 2016 for all ownerships.

A total of 79.1 Tg C of disposed solid products has accumulated between 1900 and 2016, with 74% of this associated with disposed wood products. As the accumulation of disposed paper and wood has a similar temporal pattern and the disposed wood represents the larger store, only the disposed wood pool is shown in Figure 15. For each of the ownerships disposed wood stores have steadily increased over this period, although there is evidence the rate of accumulation for disposed wood associated with harvest on federal land had declined. This is likely due the recent decline of harvests on these lands. The rapid increase in stores after 1970 is associated with the advent of landfills which have extremely low rates of decomposition. By 2016 the vast majority (99.9%) of disposed wood stores is associated with landfills; similar results occurred for disposed paper.

Total Stores

A total of 247.4 Tg C has accumulated in either wood products in use or disposal in the 1900 to 2016 period (Figure 16). The majority of these stores (68%) is in the form of products in use, however, the fastest growing store is disposed products principally in landfills. Federal harvests are the only ones where harvest led to declining stores since the 1990's. This is related to the decline of harvest on this type of forest ownership. The trend on federal forests has caused the store for all ownerships to recently decrease its accumulation rate---the post-1990 rate is approximately half the pre-1990 rate.

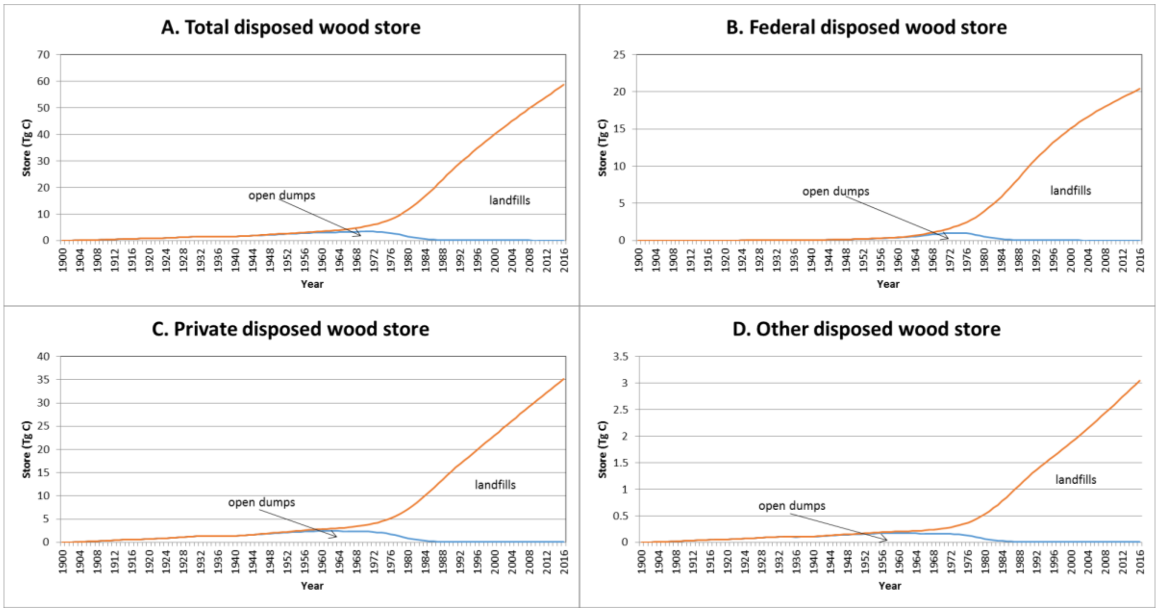

Figure 15. Stores in disposed wood 1900 to 2016.

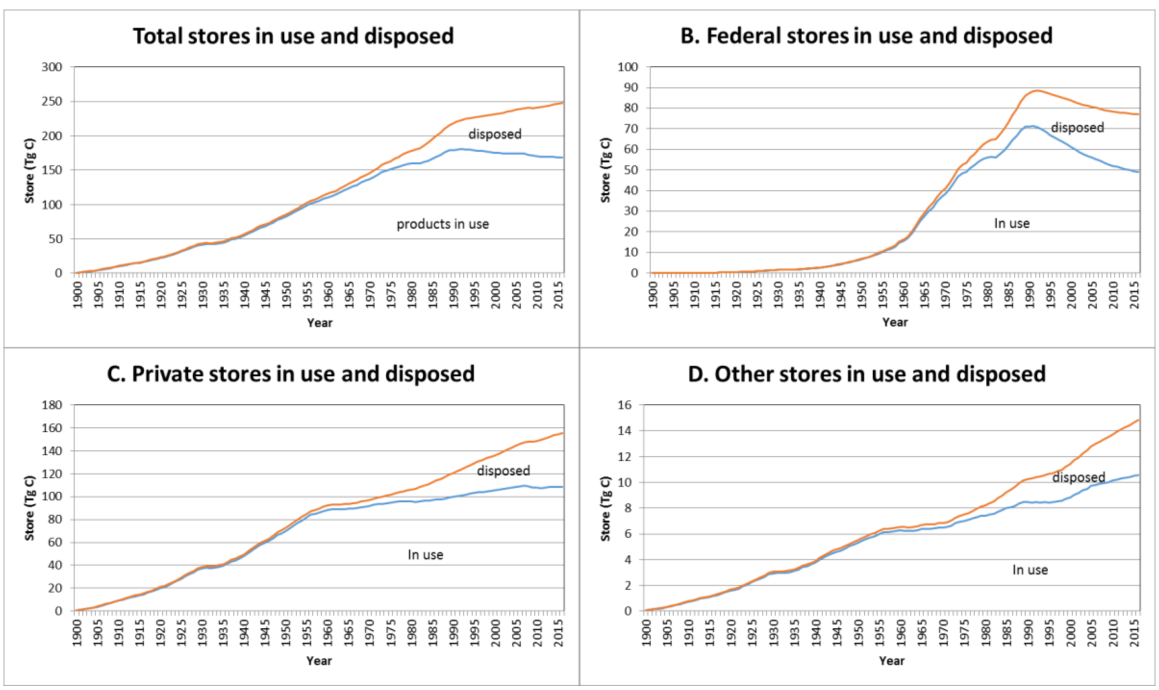

Figure 15. Store of carbon in solid wood products in use or disposed 1900 to 2016.

Overall Flows and Net Balance

Harvest, the flow providing an input to the wood products system, and losses via combustion and decomposition are largely mirror images (Figure 17). The balance of flows into and out of the wood products sector indicates that the net change in solid stores (equivalent to the net balance of flows) has been by and large positive when all ownerships are considered together. Exceptions have occurred during the Great Depression and the recession of 2008, periods when the net change in stores (or balance of flows) was slightly negative. Given that decomposition and combustion losses associated with manufacturing are large relative to those of products in use, the main driver in changes in the net balance are likely associated with variations in harvest levels.

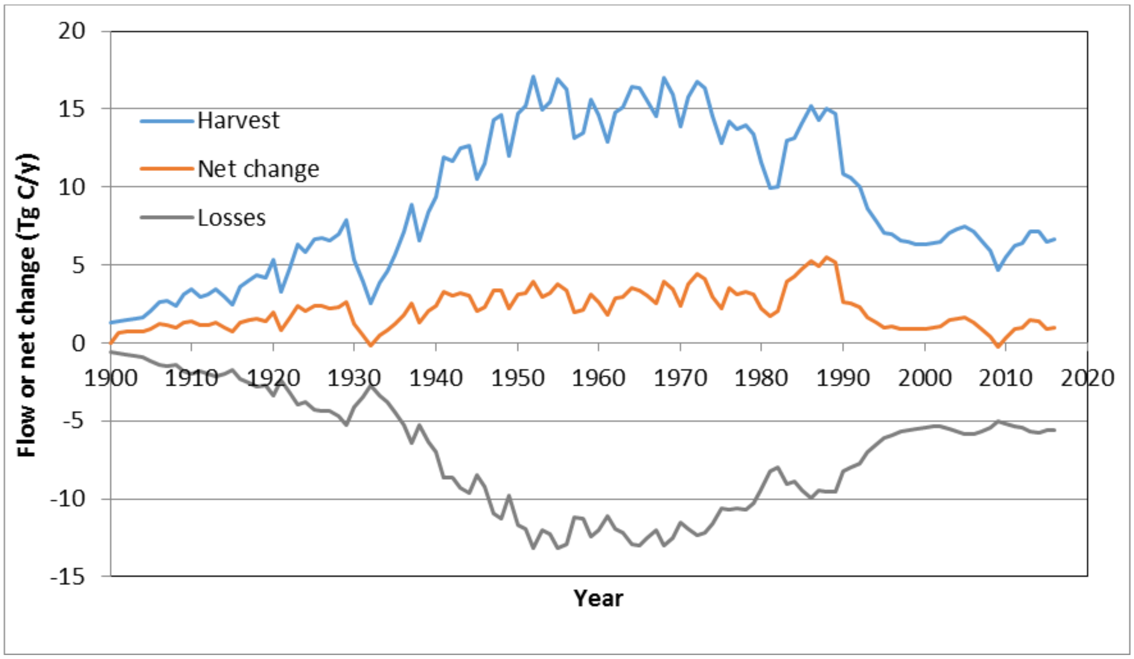

Figure 17. Flows into and out of harvest-related carbon and net change in stores (or net balance of flows) 1900 to 2016.

Accumulated Store and Cumulative Harvest

To get a rough sense of how much of the harvested carbon is retained one can compare the accumulated store to the cumulative harvest over time (Figure 18). This indicates that for all ownerships combined a total of 23.2% of all the harvest is still retained as a solid form of carbon. This proportion varies slightly among ownerships with federal, private, and other having 25.7, 21.9, and 24.9%, respectively. The lower value for private forests is likely due to the fact that harvests from these lands have occurred over a longer period than those from federal forests. This is because as pools accumulate, their net rate of increase (i.e., net change in stores) generally declines.

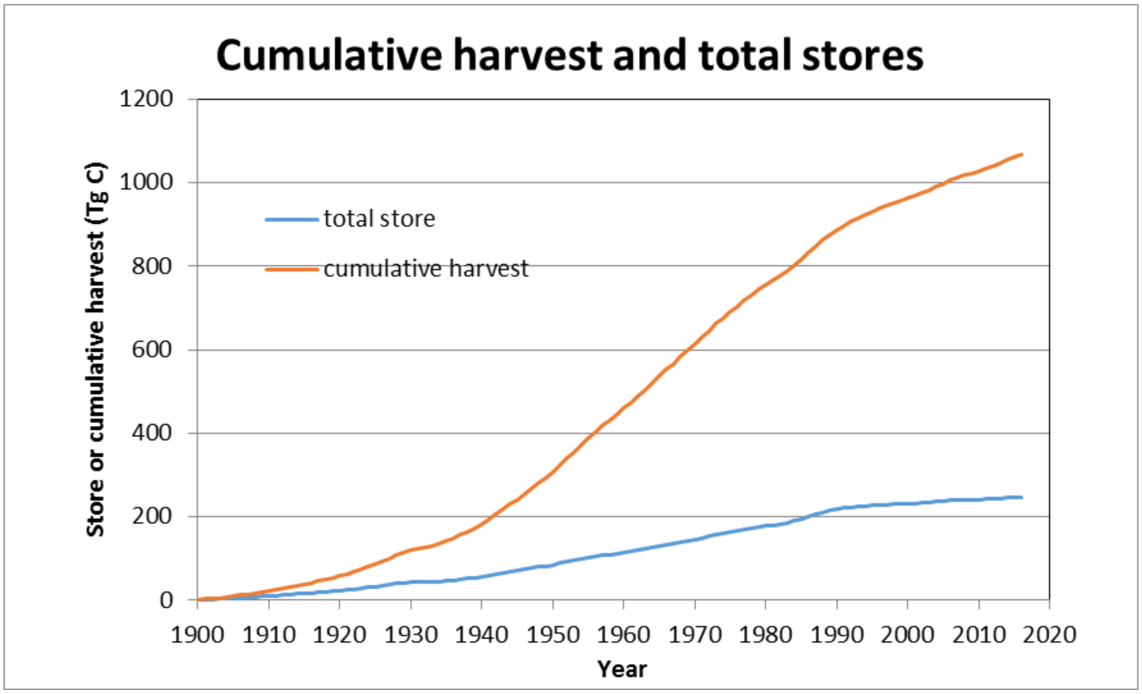

Figure 18. Cumulative harvest and store of harvested carbon in solid form of carbon 1900 to 2016 for all ownerships combined.

Net Change to Harvest Ratio (NCS to H ratio)

An important metric to help estimate the net accumulation of carbon in solid wood products in-use and disposed is the ratio of the net change in stores to harvest (NCS to H ratio). In effect this allows one to estimate the net change in stores from the harvest flow. When all ownerships are considered it can be seen that this ratio is not a constant, rather it changes over time (Figure 19). Overall there is a decline in this ratio which is driven by the fact that as stores increase so does the fraction of input that is going toward replacement of losses from older stores. This means less of the input is available for net increases in stores. There are also short-term fluctuations in this ratio which appear to be related to fluctuations in harvest. For example, notable decreases occurred in the 1930's and late 2000's. Conversely, increases occurred in the late 1980's when harvests temporarily increased.

For the 2003 to 2013 period, which overlaps the FIA inventory estimates of harvest and ecosystem stores, the overall ratio is 0.139. This indicates that the net increase in wood product solid stores is equivalent to 13.9% of the harvest during this period. For federal, private, and other ownerships this ratio for the same period was -0.659, 0.234, and 0.324, respectively. This means that the net change in products stores on federal lands is negative, declining at a rate equivalent to 69.5% of the harvest. This negative value is associated with the decline in harvests on these lands, which is relatively low compared to the pre-1990 period. The increase in stores on private and other ownerships would be equivalent to 21.6% and 31.9% of the harvest. The highest value on the so-called other ownerships is likely due to the recent increase of the harvest share this ownership represented which implies pools from these forests are in an earlier phase of accumulation than those from private lands.

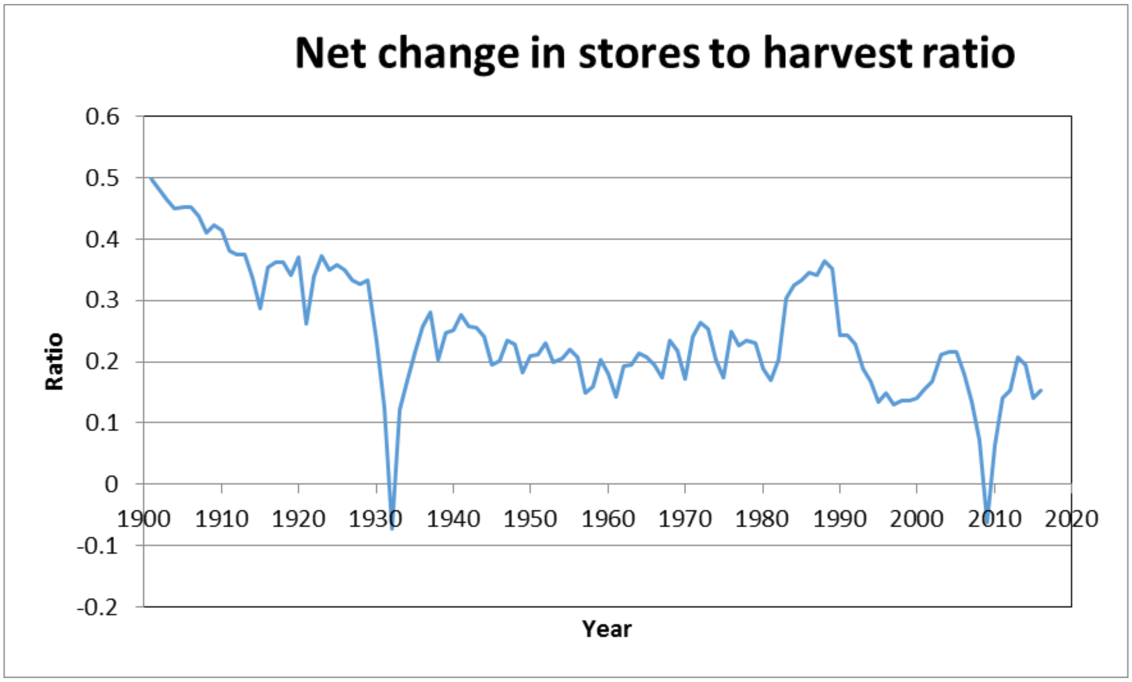

Figure 19. Changes in the ratio of net change in stores and harvest (NCS to H ratio) 1900 to 2016 for all ownerships.

Discussion

Comparison to other Methods

An alternative method that has been proposed to estimate the net accumulation of harvested carbon is to assume a 100-year timeframe and to estimate the amount of harvested carbon remaining after losses from manufacturing have been accounted. This might be called the fixed ratio method. While this is a simple way to make these estimates it is fundamentally flawed. Conceptually it turns a system with inputs and outputs into one in which there are no losses. This is despite the fact some losses are accounted for. The problem is that others are not. This turns the system that has the potential to increase, decrease, or remain constant into one in which there can only be increases (assuming there are harvests). It essentially assumes that stores can only increase; however, the store of carbon can decrease if only temporarily if inputs drop (as in the case of harvest on federal lands). Since harvests cannot be negative, there is no way for stores to decrease if the ratio is fixed and has a positive value. The more complete process-based model used here demonstrates that loss periods can and do occur. The assumption that there is a fixed fraction of harvest by which harvest related carbon increases is also clearly wrong. The process-based model demonstrates that this ratio or fraction changes over time, responding to variations in harvest amounts as well as changes in the size of the stores pool. It also indicates this ratio can be negative when stores are being lost. Finally, use of a fixed ratio will overestimate the amount of forest product-related stores. For example, if it assumed that 36% of the harvest is stored permanently, then the accumulation of product related stores between 1900 and 2016 would be 384 Tg C. The process-based model that accounts for all losses indicates the store reached 247 Tg C over the same period of time.

Temporal Trends

The temporal trends predicted by the process-based model conform to those expected by general systems theory and to those expected from the pattern of harvest, manufacturing, use, and disposal of products. Conceptually pools cannot accumulate at a steady-rate unless there is a constant input and there is no negative feedback present. Since harvests have varied over time and negative feedbacks are present in all the pools being considered, the constant accumulation of stores in harvest-related carbon is not possible. Moreover, the process-based model predicts that pools with shorter average retention times reach a steady-state faster than those with longer ones. The temporal pattern of products in-use as well as those after disposal conforms to these predictions. Hence long-term structures accumulate stores longer than short-term ones (as well as short-lived pools such as paper and mulch). Likewise products disposed in landfills accumulate stores longer than that disposed into open dumps.

Variations in harvest are clearly reflected in the accumulation of harvest-related stores and strongly influence the net balance of these stores. When harvest drops, the net balance decreases and when the drop is large or of long duration, as in the case of federal harvests, the net balance can go negative for extended periods. The steady increase in landfill stores occurs after the known shift from disposal in open dumps with high rates of decomposition and combustion to landfills with low rates of decomposition and very rare combustion. Thus while the predictions may not be correct in absolute terms (i.e., harvest could be under- or overestimated), the temporal pattern of stores changes, the proportional relationship of the various pools, and the pattern of changes in net balance (or net change in stores) by ownership and over time is likely very robust.

Average Lifespan in the Wood Products Sector

A metric that provides some sense of how long carbon remains in a pool is provided by the ratio of the store to the sum of all the flows causing losses. For solid products stores in-use and disposed the losses would be in the form of combustion and decomposition occurring in manufacturing, use, and after disposal. The mean retention time of solid products from all ownerships taken together is 43 y, that for federal lands 65 years, that for private 37 years, and that for all other ownerships is 33 years. There are several possible causes for these relationships. For one thing, the stores have not yet reached a steady state. In a phase of accumulation the mean retention time is likely to be lower than in a steady-state phase. This is probably why the other ownership group has the lowest mean retention time (the proportion of harvest from these lands has recently increased). The longer retention time for federal ownerships is likely related to the fact these stores have been decreasing. During a decreasing phase the faster components of the store are disappearing leaving materials with a longer life-span (such as those in landfills).

Energy substitution

Depending on how much waste in paper manufacturing is converted into energy between 78.5 and 108.5 Tg C of the emissions could be subject to energy substitution over the 1900 to 2016 period. This would counter the emissions related to forest harvest manufacture, use, and disposal. However, the value is lower than these totals because use of one unit of wood carbon-based fuel does not displace one unit of fossil carbon. In the case in which coal is the fossil carbon being displaced, burning wood and bark waste for energy would potentially create a 70.6 to 97.6 Tg C "offset" of emissions from manufacturing. If the fossil fuel were natural gas, then the values would roughly be half these values (i.e., 35.3 to 48.8 Tg C). One must also bear in mind if the energy being displaced was hydro-based, then the displacement would be zero (because it does not involve fossil carbon). To estimate the amount of emissions countered by energy substitution it would be necessary to estimate the mixture of energy sources displaced over time. Additionally one needs to estimate how much of the fossil carbon was used by other sectors despite not being used in the forest sector. Even ignoring those potential losses, the fraction of total carbon emissions from manufacturing, use, and disposal of forest harvested carbon "offset" by energy substitution over the 1900 to 2016 period is low, ranging between 4 to 12%. Even if the last decade is considered the amount of carbon emissions of all sorts offset by energy substitution is low (i.e., 17% for natural gas substitution and 34% for coal). Thus the majority of carbon emissions related to forest harvested carbon are going into the atmosphere regardless of whether energy substitution is considered or not.

Variation in ratio of net change in stores to harvest (NCS to H ratio)

While several of the parameters used in the model have potential to influence the estimates of stores, perhaps the one with the greatest uncertainty involves the lifespan of long-term structures such as buildings. The results described findings for the case in which the average life-span of long-term structures was 50 years. One must bear in mind that this does not mean long-term structures do not last beyond 50 years. With an average life-span of 50 years, 1% of the long-term structures would remain after 230 years. That is the maximum life-span is 4.6 times longer than the average life-span. Halving the life-span to 25 years (indicating a maximum life-span of 115 years) would decrease the NSC to H ratio by roughly 17% for private, 12% for other and 38% for all ownerships (Table 1). In the case of federal ownership the ratio would become more negative by 30%. Doubling the life-span to 100 years (i.e., a maximum life-span of 460 years) has the opposite effect. For all ownerships combined the ratio increases by 68%. The effect for the private land's ratio increases by a smaller amount (32%) and that for other ownerships it increases even less (16%). For federal lands the ratio becomes 50% less negative. This analysis indicates that doubling or halving life-span does not necessarily halve or double the ratio. The response of the ratio appears to depend on the sign of the ratio as well how long stores have been accumulating from an ownership. Despite using the 100 year life-span in this sensitively analysis it should be noted that most studies use a far lower number; typically in the 75 to 25 year range.

Table 1. Sensitivity of NCS to H ratio to life-span of long-term structures.

Long-term structures life-span (y)		NCS to H ratio (%) Ownership			
average	maximum	All	Federal	Private	Other
25	115	8.6	-85.4	17.9	28.1
50	230	13.9	-65.9	21.6	31.9
75	345	19.2	-46.7	25.4	35.5
100	460	23.3	-32.8	28.6	37.0

Another parameter for which there is uncertainty involves the life-span of carbon disposed into landfills. For the results reported it was assumed that the average life-span of this material was 200 years or a maximum life-span of 920 years. Halving or doubling this life-span changes the ratio to some degree, but the effect is limited. For example, halving the life-span of landfilled material to an average life-span decreases the ratio by 31%, whereas doubling it increases it by 18% when all ownerships are considered. One reason for the lack of responsiveness, particularly when the life-span is increased is that landfilled material has only been accumulating since the 1970's, hence there has not been enough time for these differences to be expressed fully. In comparison to the effect of long-term structure life-span, that of landfills is relatively less important.

Table 2. Sensitivity of NCS to H ratio to life-span of landfill carbon.

Long-term structures life-span (y)		NCS to H ratio (%) Ownership			
average	maximum	All	Federal	Private	Other
100	460	9.6	-81.1	18.4	28.8
200	920	13.9	-65.9	21.6	31.9
300	1380	15.6	-59.9	24.4	32.7
400	1840	16.4	-57.0	23.4	33.1

Anticipated Improvements

There are a number of ways that the current analysis could be improved. This includes:

1. Dividing the harvest into different regions within the state. Tabular data on these trends exists and if put in digital form could be used to estimate how harvested carbon has accumulated from these regions over time.
2. The estimates of the amount of manufacturing "waste" burned for energy production are only approximate. A more resolved temporal trend from the switch from "waste" incineration for volume reduction to a system with energy capture would allow a more precise estimate to be made. Additionally resolving the amount of paper manufacturing waste that is decomposed versus combusted would improve estimates given the amount of this material that is produced in paper manufacturing. To estimate the amount of energy substitution it will be necessary to couple these improved estimates of waste burned for energy recovery with a history of the energy it has replaced. It is likely that the mix of fossil fuels used as well as the proportion of non-fossil energy used (e.g., hydropower) has changed over time.
3. The data on recycling of paper and wood needs to be updated. While this is unlikely to change the results significantly, it would complete the updating process.
4. Additional sensitivity tests to examine the effect of changing the fraction in bark, life-span of minor products (mulch, paper, and short-term structures), and other parameters would provide additional insights into how robust the estimates are and where improvements could be made.

Conclusions

A process-based model of how harvested carbon is processed and stored in the solid wood products system was used to estimate the net increase in solid wood products relative to the amount of harvest for the state of Oregon's forests. The analysis shows that the net rate of accumulation of solid wood products carbon varies over time and for some ownerships contributing to the harvest the accumulation rate can be negative. For the most recent period the net change in harvest-related stores is equivalent to approximately 14% of the stem harvest. However, this metric varied with ownership and was lowest for federal lands (- 66%) and highest for land ownerships that were neither private nor federal (32%). These estimates can be used with harvest flows coming from the FIA analysis to indicate the absolute rate that stores in these pools are increasing or decreasing over time.

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