Modeling Carbon Sequestration in Harvested Wood Products

by

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Abstract

Carbon offset programs, such as that overseen by the California Air Resources Board (CA ARB), have emerged as a strategy for climate change mitigation. Offset projects sequestering carbon earn credits that can be traded on the Cap and Trade market to compensate for carbon emissions. The carbon stock embodied in harvested wood products can make up a substantial portion of the sequestered carbon in forest offset projects. In this paper, I investigate the sensitivity of the calculations for the number of credits allocated to a forest offset project. I also examine how alternative models for the decay of harvested wood products would change the amount of credits earned. The results show that the distribution of wood products produced has the greatest influence on the number of credits received, that it is important to include landfill storage in the models, and that alternative models for the change in wood product stock may improve the accuracy of the calculations.

Introduction

In this paper I consider a variety of ways in which the harvested wood products might be treated in accounting for the total number of offset credits, management changes that might alter the amount of carbon storage in wood products, and accounting strategies that would improve the accuracy of the carbon accounting to reflect the true release of carbon to the atmosphere, including the use of alternate decay functions to represent the loss of carbon from wood products. The introduction and background sections of this paper provide the context and motivation for this research. In the next sections I outline the current methods for accounting for carbon sequestration in wood products. The remainder of the paper explains the results of my own research. I compare the impact of differences in product mix on sequestration models and the impact of landfill storage, as well as the results for using different models to represent wood product decay.

In efforts to improve accounting of carbon in the atmosphere and promote mitigation strategies for climate change, keeping track of the flow of carbon stocks from harvested wood products has received increasing notice in recent years (Bowyer, et al., 2010). Cap and Trade programs and other voluntary offset programs, such as those overseen by the Climate Action Reserve (CAR), California Air Resources Board (CA ARB) and the Regional Greenhouse Gas Initiative (RGGI) allow the use of forestry projects to offset emissions from fossil fuel activities. These offset projects keep track of on-site carbon contained in the forest itself and the carbon stored in wood products as a consequence of harvests. Forest carbon stocks are increased or conserved through three types of forest projects: Reforestation, Improved Forest Management, and Avoided Conversion (RGGI, 2013; CA ARB, 2014 (a); CAR 2015).

Reforestation projects involve replanting and restoring tree cover on land that is classified as having had less than 10% tree canopy cover the last ten years. (RGGI, 2013; CA ARB, 2014 (a)). Under the CA ARB protocol, no harvesting is allowed in the first 30 years of the project (CA ARB, 2014 (a)). Improved Forest Management projects maintain or increase forest carbon stocks through a variety of ways, including (but not limited to) increasing forest productivity, increasing the age of the forest, and increasing the forest stock. Avoided Conversion projects aim to protect land at risk of conversion to non-forest cover.

In the Avoided Conversion and Improved Forest Management projects, harvests may take place yearly or less frequently depending on the management strategy set in place on the project site. In these programs that include forest harvests, a focus is often placed on increasing the onsite carbon stock through regrowth. However, the harvests produced by forests also have a vital role in maintaining this carbon stock (EPA, 2016). By using some broad assumptions and simple calculations, we can gain a picture of the importance of the harvested wood products (HWP) stock.

Let us assume that the change of the stock of carbon in harvested wood products can be represented with the equation

$$\frac{dS}{dt} = J(t) - \int_0^\infty J(t-\tau) \cdot D(\tau)\mathrm{d}\tau$$

where S is the stock of carbon in wood products, J(t) is the rate of production of the stocks in year t, D(τ) is a distribution function that describes the removal of stock through decay, recycling, landfills and other processes. If D(τ) is assumed to be the exponential distribution (the current assumed rate of decay in the Intergovernmental Panel on Climate Change (IPCC) and CA ARB protocols), the equation reduces to

$$\frac{dS}{dt} = J - kS$$

where

- J= annual production of harvested wood products, assuming a constant rate of production
- S= the total stock of carbon in harvested wood products
- k= the rate at which this stock is decaying.

The kS term then, represents the annual decay in proportion to the existing stock. If J is representing the sustainable annual HWP production, then we could also think of J as

$$J = m \cdot \frac{T_{\text{forest}}}{n}$$

where T_{forest} represents the total carbon contained in the live forest, n the number of years in the forest's rotation cycle and m a processing efficiency factor, representing the fraction of total harvest carbon that ends up in products, (m<1).

If a forest has a rotation cycle of n years, we can assume that the average portion of the forest that is cut down for the production of wood products each year is $\frac{T_{\text{forest}}}{n}$. Of this portion of the forest that is harvested, not all of the mass will be present in the harvested wood products. This variable will depend on the type and size of tree, the desired product mix, and the processing efficiency.

If we assume that the stock of carbon in the wood products has a first order decay/removal rate, we find that the this steady state stock (S) of HWP is $S = \frac{\text{J}}{k}$.

$$\begin{aligned}\frac{dS}{dt} &= J - kS\\ 0 &= J - kS\\ J &= kS\\ S &= \frac{J}{k}.\end{aligned}$$

where

- $k = \frac{\ln(2)}{H}$
- H= Product half life.

Therefore, the total carbon in the forest and the total carbon in the stock of harvested products can be compared with the equations:

$$S = J \cdot \frac{H}{\ln(2)} \quad \text{and} \quad T_{forest} = \frac{J \cdot n}{m}$$

A conservative estimate for the half life of all products that are produced from a forest might be 12 years (see Table 1). If we assume that a forest has a rotation cycle of about 30 years, and assume a mill efficiency value of 0.584, (the average mill efficiency value for the southeastern states (CA ARB, 2014 (b))) we end up with the following results.

$$S = J \cdot \frac{12}{\ln(2)} \text{ and } T_{forest} = \frac{J \cdot 30}{0.584}$$

$$S \approx J \cdot 17.31 \text{ and } T_{forest} \approx J \cdot 51.37$$

This is a very simplistic model, but it suggests that the carbon stored in these products can be of the same order of magnitude as the carbon within the forest. This possibility reveals the need for accurate modeling and accounting of these forest product stocks. If live forest carbon stocks and harvested wood product carbon stocks are storing comparable amounts of carbon, they should be valued comparably in offset programs.

Background

The California Cap and Trade Program and other mitigation programs include carbon offsets as an avenue for compensating for emissions. IPCC methodology also outlines methods for accounting for carbon sequestered in harvested wood products.

The California Cap and Trade market was established to "use a market-based mechanism to lower greenhouse gas emissions" (Center for Climate and Energy Solutions (C2ES), 2014). Governments or corporations set a target, or 'Cap', for emissions reductions. The regulator of the market then allocates an allowance for carbon emissions consistent with this target (International Emissions Trading Association, 2015; C2ES, 2014). In the state of California, a portion (8%) of total emissions can be offset by purchasing carbon offsets produced by offset projects (CA ARB, 2012, 2013, 2014 (a)) to meet this allowance. This represents the trade aspects of the market. An offset is defined by the CA ARB to be "A credit that represents a reduction or removal of greenhouse gases by an activity that can be measured, quantified, and verified" (CA ARB, 2012). Some project owners can opt into participation in the system, but large electric power plants and large industrial plants and fuel distributors are required to comply with the California Cap and Trade program (C2ES, 2014).

Currently, forest projects represent one category of these offset projects in the California system. Only 21% of all offset projects are forest projects, but as of March 23, 2016, 62% of offset credits were issued to forest projects (CA ARB, 2016). A forest owner may register a project in a CA ARB-approved registry and earn offset credits that can be sold or traded on the carbon market by complying with the CA ARB protocol. (CA ARB 2012, 2013, 2014(a)) Forest projects can fall under the categories of Reforestation, Improved Forest Management or Avoided Conversion (ARB, 2014). As of October 2015, 87% (48 out of 55) of all CA ARB forest carbon offset projects fall under the Improved Forest Management category, in which a forest owner manages their forest in such a way that a greater amount of carbon is sequestered in the forest and the wood products resulting from the forest's harvest (CA ARB, 2014).

The CA ARB protocol outlines specific methods for accounting for the carbon sequestration achieved by these projects, including models for measuring the carbon stored and sequestered in harvested wood products. Forest project owners receive credits when they can verify that their actions have resulted in carbon sequestration above and beyond what typical practices would have produced. To make this comparison possible, baseline values for carbon sequestration are also modeled.

By selling the right for companies to emit carbon dioxide and other greenhouse gases, the cap and trade market creates "a market and a price for emissions reductions" (C2ES, 2011). While the overall goal of the program is to reduce net carbon emissions, this goal is pursued by quantifying the cost of emissions and benefit of sequestration and lowering the "cap" portion of the market.

This means that the protocol is not only modeling the flow of greenhouse gases, but also the flow of the money associated with their emissions, quantifying the monetary value of sequestration and reduction. While the CA ARB protocols work to accurately account for the carbon flows, some aspects of their protocol also work to incentivize participation in the market. All examples within this paper are taken from the November 2014 draft of the CA ARB protocol.

IPCC Reporting

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Program (UNEP) and the World Meteorologic Organization (WMO) for the purpose of gathering global information on climate change and issuing reports synthesized from this data (IPCC, 2015). All reporting authored by the 195 panel members has gone through an extensive review process. This panel's goal was to consolidate scientific information (Union of Concerned Scientists, 2008). Although the IPCC's directive is primarily scientific, the reports issued every six years are intended to inform policy makers around the world. In this paper, I am focusing on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. These guidelines provide methodology for calculating the carbon sequestration in harvested wood products. For in-use wood products, the fraction that remains in-use at any time is calculated "based on estimated half life and associated decay rates of harvested wood products from use assuming first-order [exponential] decay rates."

A first order rate of decay is assumed, but the guidelines recognize that there are a variety of possible modeling choices, and express that they have no preference (IPCC, 2006). Equation 12.1 in the 2006 IPCC guidelines provides a method for the estimation of carbon stock and its annual change in HWP pool of the reporting country, where the carbon sequestered in the current year is based on the previous year. The IPCC provides default half life values of 30 years for solidwood products and two years for paper products for these estimations.

When we compare the models used by the CA ARB and the IPCC, we can see some structural similarities (Kenneth Skog was involved in the creation of each), but also differences in modeling choices and motivation. The driving force behind the IPCC's models was a desire for a scientific representation of the carbon flow. While the CA ARB model is also scientifically motivated, as it is a part of a protocol with economic implications, its motivation is to not only track the flow of carbon, but incentivize and reward sequestration.

While the CA ARB includes a high level of detail in their calculations, the IPCC guidelines give little preference to modeling choices, and only provide one estimated half life for all hardwood products. In addition, the hundred year storage factor is a key aspect in the CA ARB calculations, whereas the IPCC calculates year by year, not in 100 year increments. Both assume first order decay of the products.

CA ARB Approach

As harvested wood products represent a large stock of carbon, this paper examines the assumptions, data and calculations that are used for modeling the stock of carbon in harvested wood products in the

CA ARB protocol. Carbon stored in harvested wood products can be an important part of the carbon offset forest projects and resulting credits traded on the carbon market, and the preliminary nature surrounding the IPCC guidelines indicate a need for this type of analysis.

The CA ARB protocol for forest offset projects provides a method for calculating the carbon stock in an estimated baseline and in actual harvested wood products for Improved Forest Management and Avoided Conversion projects. The basic computational process is illustrated in Figures 1 and 2.

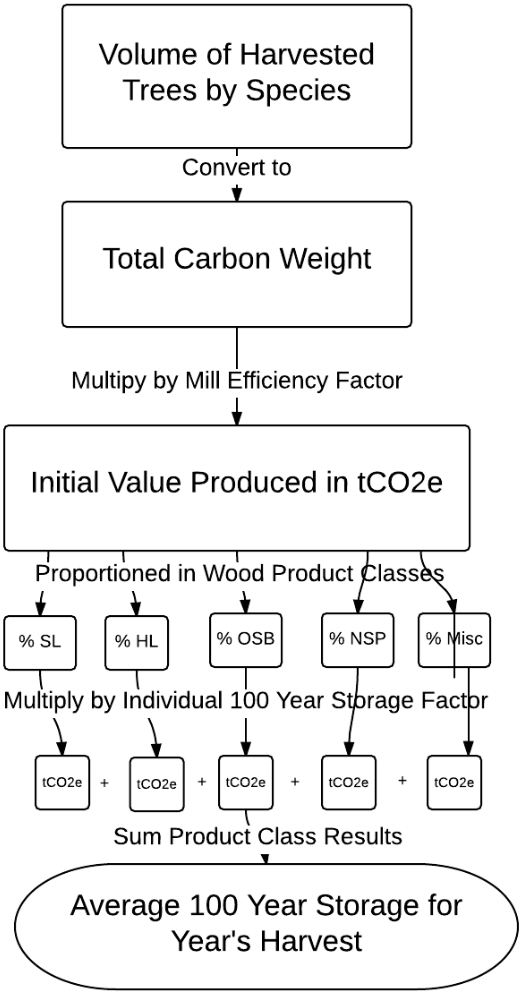


Figure 1: This flowchart demonstrates how to calculate the tons Carbon Dioxide equivalent (tCO_2e) storage in harvested wood product storage. Examples of wood product classes include Softwood Lumber (SL), Hardwood Lumber (HL), Oriented Strandboard (OSB) and Nonstructural Panels (NSP)

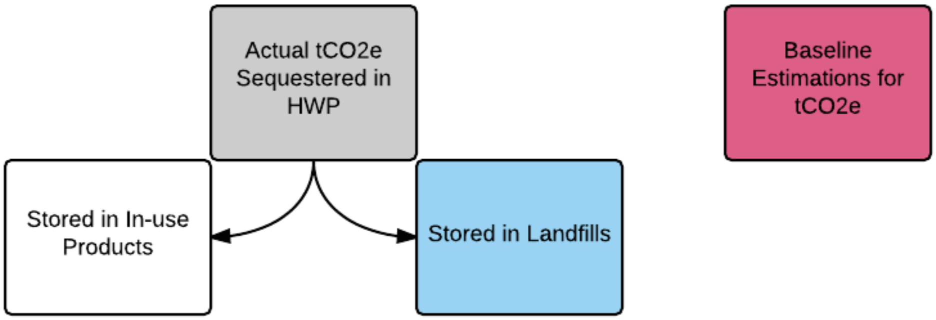


Figure 2: The flowchart above illustrates the CA ARB protocol for rewarding credits to registered project owners.

This storage is calculated using the actual harvest volume and the baseline harvest volume. For the actual harvest and baseline harvest estimates, both the in-use carbon storage and the landfill carbon storage are calculated. CA ARB credits must be real, verifiable and permanent (CA ARB, 2014(a)). To earn credits, it must be verified that the tCO_2e stored in the harvest is greater than the estimated baseline tCO_2e storage. If the in-use carbon storage is less than the baseline carbon storage, projects owners are credited with the difference between the sum of the in-use and landfill credits and the baseline estimations. If, however, the in-use carbon storage is greater than the baseline carbon storage, the project owners are credited with the difference between the in-use product storage and the baseline estimations. In other words, the carbon in landfills is treated differently depending on how much carbon is sequestered through the project's in-use product storage in that year.

The protocol provides a 100 year storage factor for each wood product class to use for the calculation of credits for harvested wood products. The 100 year average storage factors in Table 2 represent the mean value of the fraction of carbon remaining in the products each year, over 100 years. As it is difficult to define “permanence” the 100 year storage factor is used as a proxy for permanent sequestration.

Each wood product class is made up of a different proportion of wood products, such as houses, railroad ties, or furniture. Each of these products has a different estimated half life shown in Table 1, and contributes to the overall 100 year storage factor value in Table 2.

Type of Product	Half Life
Single Family Home	100
Multi-Family Home	70
New Building Construction	67
Furniture, Residential upkeep and Improvement	30
Railroad const. and repair, exports and misc. products	12
Shipping	6

Table 1: Half lives of harvested wood products. (Smith, et al., 2006)

Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
100 Year Storage	0.463	0.250	0.484	0.582	0.380	0.176	0.058

Table 2: 100 Year Storage Factors (Table C.2. CA ARB, 2014(a))

As noted above, the 100 year average storage factor represents the mean value of the fraction of carbon remaining in the products each year, over 100 years. This can also be written as

$$\frac{1}{100} \cdot \sum_{n=1}^{100} x_n$$

where x_n represents the fraction of carbon remaining in the product after year n. This value is calculated for in-use wood products as well as wood products in landfills, for every wood product class.

The fraction of carbon remaining in each year for each wood product is calculated with the formula

$$x_n = x_0 \cdot e^{-\alpha \cdot n}$$

where n represents the year in consideration since production (with x_0 being the initial year's production amount) and $\alpha = \frac{\ln(2)}{H}$, where H is the product half life. This is a standard formula for exponential decay.

The 100 year storage factors for the product classes are found by computing a weighted average of the storage factors for the individual wood products. The weights correspond to the proportions of products within each class. A similar process is followed for calculating the 100 year storage factors for wood products remaining in landfills.

The number of credits allocated to a project is calculated based on the difference between the projected baseline amount of carbon remaining in harvested wood products as a result of the year's harvest and the estimates for actual remaining carbon based on the actual year's harvest, the "Harvest Volume" in tCO_2e. The baseline is estimated at the beginning of the project and is estimated out for 100 years (CA ARB, 2014(a)).

Sensitivity of the Allocation of Product Data into Classes

The 100 year storage factors are indirectly based on the half lives of wood products. We will use the hardwood product class storage factor as an example to illustrate how wood product half lives are used to calculate these values. To calculate the 100 year storage factor for a wood product class, we need to know what kind of products are made out of that type of wood, and what kind of half life those products have. Figure 3 provides a visual for this computation. A portion of Hardwood Lumber is used for miscellaneous uses, which is not included in Table 3 or Figure 3.

Approximate Breakdown Percentage	Primary Use	Half Life (years)
3.9%	Single Family Home	100
2.8%	New Construction	67
4.7%	Residential Repair	30
9.8%	Furniture Production	30
21.4%	Exports	12
4.7%	Railroad Construction	12
35.0%	Shipping Pallets	6

Total weighted half life: 21.106 years

Table 3: Uses for Hardwood Lumber and the half life for the wood product class (McKeever, 2009)

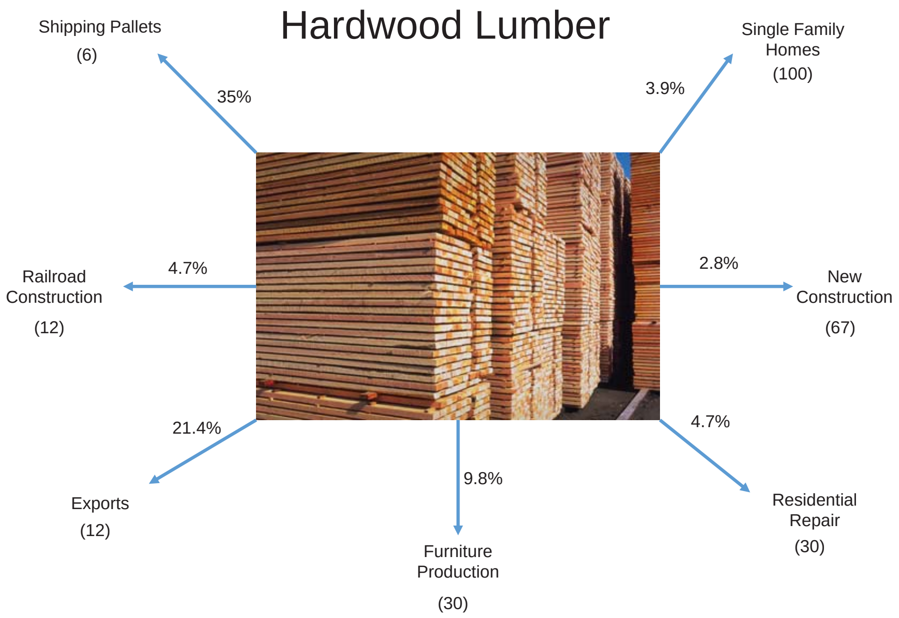


Figure 3: The distribution of Hardwood Lumber into different product types, each with a different half-life. (McKeever, 2009)

Each type of product is typically a product of a variety of wood product classes. Table 4 represents the proportion of each wood product class that goes into the construction of single family homes. We can see that a very large percentage of Oriented Strandboard (OSB) goes towards the construction of single family homes. Because these homes have such a long half life (100 years, as seen in Table 2), they cause the Oriented Strandboard product class to have a high 100 year storage factor (0.582, as seen in Table 1), as over 55% of all OSB is used to produce homes.

	Product				
End-use	Softwood Lumber	Hardwood Lumber	Softwood Plywood	OSB	NSP
Single Family Homes	33.1%	6.7%	19.4%	55.3%	18.6%

Table 4: Single Family Homes (McKeever, 2009)

Consequently, a change in a product's half life can make a difference across all 100 year storage factors for all wood product classes. It is important, therefore to consider the possible impacts that various changes, such as building codes might have on these storage factors. For example, there have been studies done comparing the impact of greenhouse gases between concrete and wood-framed buildings (Gustavsson, et. al 2005). If there were to be a policy change for building codes based on this, then a switch between materials, such as using wood rather than concrete to frame buildings, could drastically change the mean lifetime of the wood products. An increased proportion of hardwood and softwood lumber would be used for frame constructions. The increased demand for lumber in home construction may cause alternative materials to be used for other products, or for lumber to become the primary product produced by the mills. These changes to the half lives, wood product classes, and wood product distributions among harvests could greatly affect the 100 year storage factors. For this reason, data should be kept as current as possible.

Sensitivity of Harvest into Classes

As we can see in Table 1, different wood product classes have very different 100 year storage factors. This is because certain wood product classes (e.g. Oriented Strandboard) are used to produce longer-lived end products. This means that the overall storage factor for a harvest can differ by a lot depending on which products are produced from the harvest. A large harvest could have a smaller amount of carbon stored in the long term than a smaller harvest with a different distribution of wood product classes A forest owner may or may not have much choice in this matter, but their credit allotment is significantly impacted by this. We can get a sense of the magnitudes involved through a re-analysis of CAR project 973. Here, in Tables 5, 6, and 7, we can see that while the second case involves 51,473 tCO_2e more processed by the mill, there is a only a 6,214.5 tCO_2e difference in "permanent" carbon storage.

The total percentage of stock represents the amount of stock that will be credited as permanent storage, as defined by the CA ARB. This is found by multiplying the percent in each class by the storage factor for each class and summing them together. The same process is applied to find the total tons CO_2 equivalent stored permanently.

Comparison of Cases:

Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
% of harvest in class	0.3%	9.0%	0.0%	78.7%	2.1%	10.2%	0%
Tons CO_2e in class	213	7571	2	65492	1568	8155	0

Credits Received

tCO_2e Harvested	tCO_2e Stored	Fraction of Stock
83001	42152.5	0.507855

Table 5: Calculations of permanently sequestered carbon according to 100 year storage factors for various distributions applied to reporting taken from CAR project 973. Note that with this breakdown of wood product classes, over half of the tCO_2e processed is seen as permanent, still sequestered in the wood after 100 years.

Wood Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
% of harvest in class	18.0%	50.0%	0.2%	16.0%	14.0%	2.3%	0.0%
Tons CO_2e in class	24784	67120	233	21358	18525	2454	0
Storage Factors	0.463	0.250	0.484	0.582	0.380	0.176	0.058

Credits Received

tCO_2e Harvested	tCO_2e Stored	Fraction of Stock
134474	48367.0	0.359676

Table 6: Calculations for permanently stored carbon according to different distributions. Although this harvest is much larger, only about 36 percent of the tCO_2e process will still be sequestered in 100 years. Reporting taken from CAR project 973.

Credits Received

	tCO_2e Harvested	tCO_2e Stored	Fraction of Stock
Case I	83,001	42152.5	0.507855
Case II	134,474	48367.0	0.359676
Difference	217,475	6214.5	0.148179

Table 7: A comparison of the two projects

The categorization of harvests into wood product classes is determined for each species and based on regional estimates (CA ARB 2014 (a), (c)) If an individual project wishes to report values other than the typical regional amounts, they may report this with third party verification. If either of these are not possible, the entire harvest is reported as miscellaneous. (CA ARB, 2013).

Secondary Uses

It is clear from the 100 year storage factors that not all carbon is stored permanently. Because of this, the possible end of life destinations must also be considered. Possible end of life destinations for wood products include landfills, fuel, mulch, or the reuse/recycling of the product. Each of these outcomes has a different impact on the total carbon storage. In general, we can say that when a product stops contributing to the carbon stock of harvested wood products, it is either oxidized or goes on to a secondary usage. Because landfills can prevent the oxidation process, this end of life destination can result in the continued conservation of carbon stocks, and is worth further attention. The CA ARB protocol does not account for any other possible end of life uses, indicating that further research should be done to account for how end of life uses such as mulch, fuel, and reuse/recycling might affect the carbon storage of products or displacement of fossil- fuel related emissions.

Landfill Storage

In the CA ARB protocol, a project can only claim offset credits from carbon stored in landfills if the forest project's actual harvesting volumes are below their estimated baseline harvesting levels (CA ARB, 2014 (a)). If these credits are included, they are accounted for through a process similar to that for the in-use harvested wood products, as seen in Figure 1. Table 8 shows the 100 year storage factors for products in landfills.

Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
100 Year Storage	0.298	0.414	0.287	0.233	0.344	0.454	0.178

Table 8: The 100 year storage factors for the carbon storage in products in landfills (Table C.3., CA ARB, 2014(a))

As the 100 year storage factors in Table 2 are used to calculate the "permanent storage" for in-use wood products, these storage factors are meant to enable us to calculate the average wood product carbon stored in landfills over 100 years.

When we add the storage factors from Table 8 to the storage factors in Table 2, we can see the total average fraction of carbon that will be stored over the next 100 years from the present year's harvest. As mentioned previously, these are summed to represent the total average carbon storage in wood products over 100 years for a given harvest volume. We can use this information to create Table 9, a new 100 year storage factor table.

Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
100 Year Storage	0.761	0.664	0.771	0.815	0.724	0.630	0.236

Table 9: The total amount of carbon stored, in products in-use and in products in landfills

This means that over the next 100 years, between an average of 63 and 81% of the carbon in harvested wood products (excluding paper) will remain stored on earth, either in products or in landfills, each year. The CA ARB's decision to only occasionally account for carbon stored in landfills is one that doesn't appear to make scientific sense. The difference in the number of credits as a result of including or excluding landfills storage can be seen below in Table 10, a re-analysis of CAR Project 993.

Wood Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper	Total
% of harvest in class	70%	0%	28%	0%	0%	0%	2%	100%
Tons CO2e in class	11938.5	0	4775.4	0	0	0	341.1	17055
In-Use Storage Factors	0.463	0.250	0.484	0.582	0.380	0.176	0.058	
Landfill Storage Factors	0.298	0.414	0.287	0.233	0.344	0.454	0.178	

Credits Received

	Percentage of Stock	tCO2e	cost (\$12.91/ tCO_2e)
In-Use products	0.46078	7858.6029	\$101,454.56
Landfill Storage	0.29252	4988.9286	\$64,407.07
Total Storage	0.7533	12847.5315	\$165,861.63

Table 10: Number of credits including landfill storage vs. number of credits without landfill storage for CAR project 993.

Not only is this important to account for from a scientific aspect, but it makes a difference in the markets and financial incentive for offset project owners. As of December 1, 2015, the price of one tCO_2e was \$12.91 (Climate Policy Initiative, 2015). For this specific project, landfill storage inclusion represents a difference of \$64,407.07 in earnings.

Decay Distributions

In order to calculate the 100 year storage factors, it is necessary to know what fraction of the original carbon stock remains in each year. To find this, a model must be used to represent the amount of decay that occurs each year.

Exponential

As mentioned previously, exponential decay has been the standard model historically used for the release of carbon from harvested wood products. This model was chosen for its simplicity and for the lack of a clear alternative. To create the model for a product, the half life is the only information needed. With the limited amount of data available, this has been an understandable choice of model.

When modeling with the exponential distribution, as in Figure 4, one makes the implicit assumption that the product (or a pool of products) will decay most rapidly in its first years of use, with less decay occurring each subsequent year.

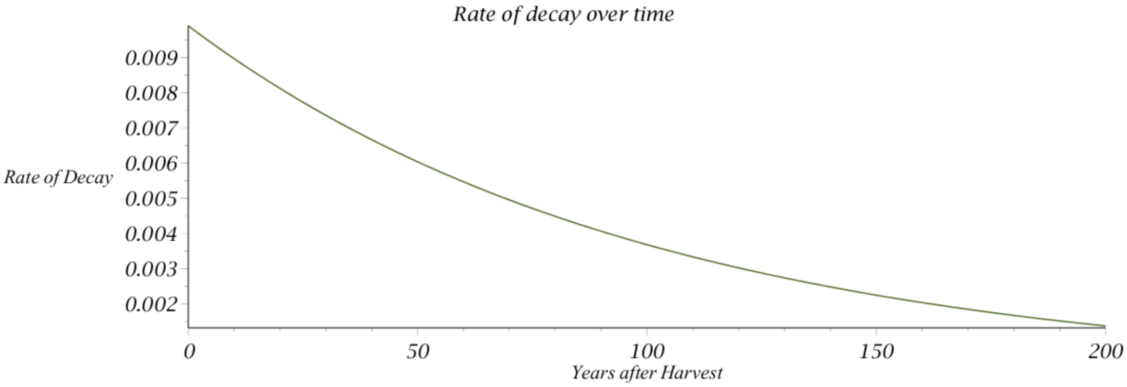


Figure 4: Rate of decay over time according to exponential distribution

In figure 4 we can see a graph of the rate of decay for an object with a 70 year half life, such as an apartment complex. This shows that the decay will be most rapid in the first years after production, with less decay occurring in later years.

It is important to remember that the rate of decay indicates the speed at which the decay is occurring. While this is possibly an appropriate assumption for fuel or short-lived products, such as paper, it does not accurately represent the lifetime and decay of longer lived products that do not decay most rapidly in the first years after production.

Gamma Distribution

In Marland et al., 2010, it is argued that the gamma distribution is a much more qualitatively accurate model to use for modeling the decay of long-lived wood products. For example, it is an intuitive assumption that within a group of pieces of furniture, few pieces ought to be oxidized (e.g. decay or be burned) in the first years after production, otherwise they might be considered to be a poorly made product. We would then assume that the rate of decay would increase as time goes on and peak around the time of the half life. The use of the gamma distribution allows us to alter the parameters that dictate the shape of the curve such that our default assumption is not that a product will decay most quickly in its first years.

The rate of decay then might look like Figure 5,

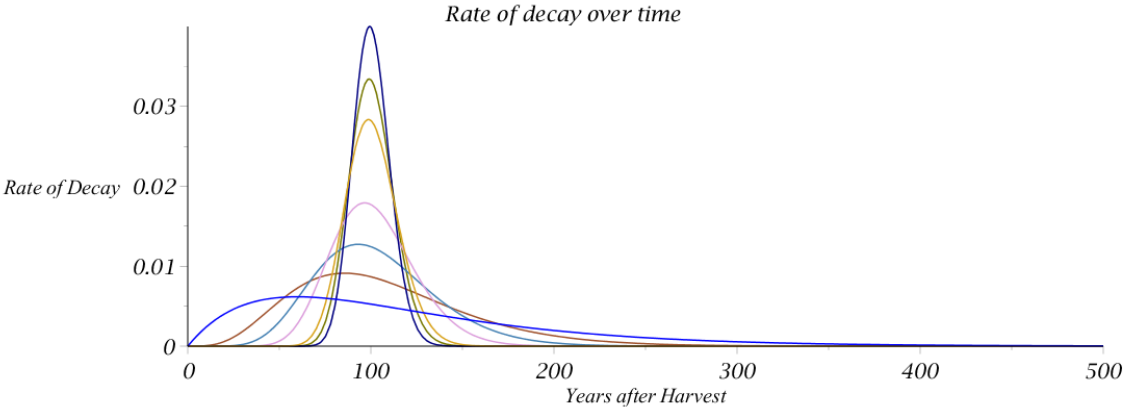


Figure 5: Rate of decay over time for products with a 100 year half life.

The difficulty in modeling with the gamma distribution is that it is a two-parameter distribution, of the form $\int_0^n \frac{1}{\Gamma(k)\theta^k} x^{k-1} e^{-\frac{x}{k}} dx$, where Γ(k)=$\int_0^\infty x^{k-1} e^{-x}$. To use the gamma distribution, data points must be available for us to define k and θ. In this distribution, the k value dictates the general shape of the curve, and the θ value dictates the scale.

Some shape values associated with different values of k:

- If $k = 1$, the function is decreasing.

- If k >1, the function increases, then decreases with a mode at $k-1$.
- If 0< k ≤1, the function is concave upward.
- If 1< k ≤2, the function is concave downward, then upward.
- If k >2, the function is concave upward, then downward, then upward again.

The parameter θ does not change the shape of the function, but scales the graph horizontally and vertically.

If we had access to another data point in addition to the half-life, such as the year of maximum decay, or the 95% decay period in years (as used in Marland et al., 2010), we could find appropriate k and θ values.

It is worth noting that the exponential distribution is a one-parameter simplification of the Gamma distribution. By fixing k=1, the rate of decay can be modeled as $\int_0^\infty \frac{1}{\theta}e^{-x}dx$,the exponential distribution. It is, however, not the only one-parameter simplification of the gamma distribution.

Introduction of Alternative Distributions

The chi-squared, standard gamma and k=2 distributions are all alternative one-parameter simplifications of the gamma distribution that can be used to model the decay of a pool of harvested wood products.

In considering these distributions as alternatives, we examined a range of k and θ values that produce decay curves representing the same half life. These were determined through setting one parameter value and changing the other value until an equal half life was obtained to four decimal places. We examined possible k and θ values for products with a variety of half-lives, with k values ranging from 0.1 to 1000 and θ values ranging from 0.000594 to 168500. A selection of these curves are shown in Figure 5. We found that the chi-squared, standard gamma and k=2 distributions were representative of the typical shapes found with a decay curve that matched our intuitions about product decay. As the set parameters are integer values, these distributions are also comparatively simple.

As mentioned previously, the exponential distribution is a form of the gamma distribution with k=1. This means that the function is constantly decreasing and concave up. We also evaluated a distribution we called the k=2 distribution, that results from setting the shape value, k=2 and varying the theta parameter. This means that our function will increase until a certain peak, then decrease. The distribution is not a named distribution, so we refer to it simply as k=2.

The standard gamma and chi-squared distributions are common statistical distributions often used in representing decay, and also come from the gamma distribution. In the chi-squared distribution, θ is set to be equal to 2 and the k (shape) parameter is varied. In the standard gamma distribution, $\theta = 1$, and the shape parameter is varied.

From our observations, the exponential decay is a convenient simplification, but represents an extreme in the range of possible simplifications of the gamma distribution. This extreme representation of decay, which would be very appropriate for modeling very short lived products, such as fuel, is currently applied to all wood products. These alternative distributions can be modeled with the same data, but are less extreme in their structure.

In Figure 6, we can see that the chi-squared and standard gamma distributions model the majority of the decay of a product happening around the time of the product's half life.

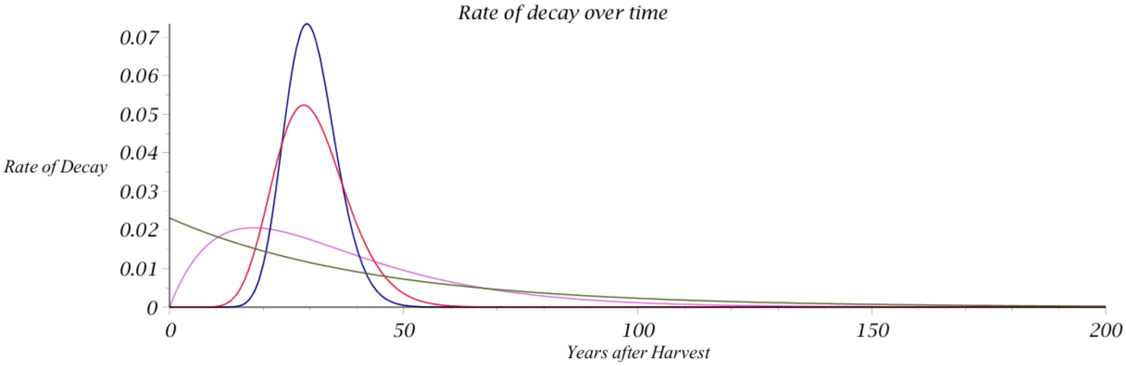
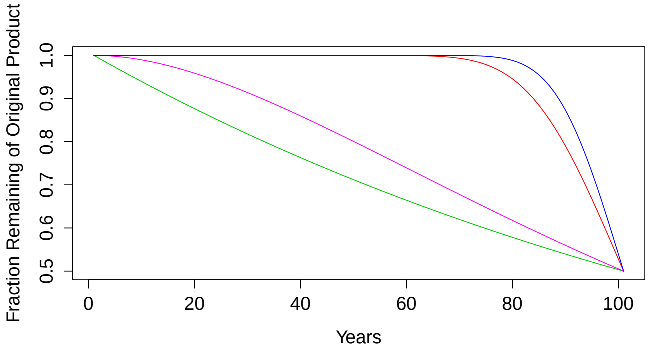
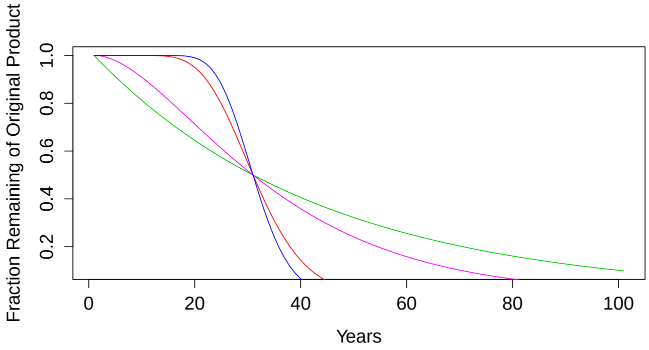


Figure 6: A plot of the decay curves for a piece of product with a half life of 30 years. The exponentia decay curve appears in green, the k=2 appears in pink, the chi-squared in red and the standard gamma in blue.

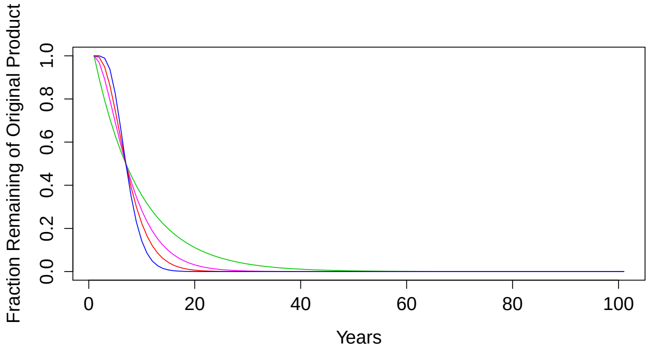
In Figure 7 we can see how the different rates of decay result in different amounts of carbon remaining in the products in each year.



(a) A plot of the fraction of initial carbon amount remaining in the product in each year, over 100 years for products with 100 year half lives.



(b) This graph shows the fraction remaining of the original product in each year for a variety of gamma distributions with the same 6 year half life



(c) This graph shows the fraction remaining of the original product in each year for a variety of gamma distributions with the same 30 year half life.

Figure 7: Here, the exponential distribution is seen in green, the k=2 distribution in pink, the chi-squared distribution in red and the standard gamma distribution in blue.

As we can see through these graphs, as the lifetime of a product decreases, the differences between the different distributions lessen.

Quantitative Results of Implementing Other Distributions

As mentioned previously, the 100 year storage factors are determined by averaging the fraction of carbon remaining in each year over 100 years.

$$\frac{1}{100} \cdot \sum_{n=1}^{100} x_n$$

$x_n =$ the fraction of carbon remaining in the product after year n.

To compute new 100 year storage factors for the other distributions, I followed a three step process.

1. First, I found the appropriate parameters to model the rate of decay for each half-life.

2. Using these distributions, I determined the fraction of carbon remaining in each year with the equation with $\mathrm{x}_n = x_0 \left(1 - \int_0^n \frac{1}{\Gamma(k)\theta^k} x^{k-1} e^{-\frac{x}{k}} dx\right)$ and used these fractions to determine the 100 year storage factor for that specific half-life.

3. Once the 100 year storage factors were found for each half life, they were combined in appropriate proportions, as seen in Table 3 and Figure 3, to create the storage factors for each wood product class.

	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
Exponential Distribution	0.463	0.250	0.484	0.582	0.380	0.176	0.058
K=2 Distribution	0.469	0.229	0.489	0.610	0.363	0.147	0.058
Chi-Squared Distribution	0.509	0.215	0.529	0.697	0.359	0.130	0.058
Standard Gamma	0.512	0.213	0.532	0.705	0.358	0.127	0.058

Table 11: Comparison of 100 year average storage factors for different decay distributions.

We can see in Table 12, that a change in the decay distribution results in much higher 100 year storage factors for wood product classes that rely on longer lived products, such as Oriented Strandboard. We see some decreases in storage factors for wood product classes with shorter lived products, such as

Hardwood Lumber, Nonstructural Panels and miscellaneous products. This corresponds to the graphs in Figure 7. As paper has such a short half life of two years, there were no significant changes between choice of distribution.

As we see in Table 14 below, a change from using the exponential to the standard gamma distribution could cause a 17% increase in credits given for a chosen mix of harvested wood products. The exact impact that a change in-use of distribution would make depends on the specific mix of product classes produced by a harvest. Tables 13 and 14 show the possible impacts of a change in distribution choice.

Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
% of harvest in class	0.3%	9.0%	0.0%	78.7%	2.1%	10.2%	0%
Tons CO_2e in class	213	7571	2	65492	1568	8155	0

Table 12: A sample harvest distribution among wood product classes, corresponding to the examples in Table 5

Credits Received

	Percentage of Stock	tCO_2e	Cost Comparison
Exponential	0.507855	42152.4729	\$544,188.43
K2	0.524704	43550.9567	+\$18,054.42
Chi-Squared	0.590215	49087.5913	+\$89,532.37
Standard Gamma	0.596013	49569.8052	+\$95,757.76

Table 13: Credits received as a result of implementing new models for decay. Calculations based on December 1, 2015 price of \$12.91 per tCO_2e

We can see in these examples that our choice of the decay distribution makes a great deal of a difference when we are working with a harvest where the distribution is more heavily weighted toward long lived products. While a change in distribution generally results in an increase in credits received, this is not always the case, for reasons explained above.

Product Class	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
% of harvest in class	18.0%	50.0%	0.2%	16.0%	14.0%	2.3%	0.0%
Tons CO_2e in class	24784	67120	233	21358	18525	2454	0

Table 14: A sample harvest distribution among wood product classes, corresponding to the examples in Table 6

	Percentage of Stock	tCO_2e	Cost Comparison
Exponential	0.359676	47294.37133	$624,418.88
K2	0.351699	47294.371335	-$13,848.55
Chi-Squared	0.364948	49076.01735	+$9,152.51
Standard Gamma	0.365565	49158.98781	+$10,223.65

Table 15: Credits received as a result of implementing new models for decay. Calculations based on December 1, 2015 price of $12.91 per tCO_2e

Reference Data

When the 100 year storage factors were calculated for the CA ARB Protocol, the calculations were based on 1998 data on the distributions of products within each product class. (McKeever, 2002). As manufacturing changes are made over the years (i.e, less railroad ties manufactured and more furniture produced), there is a potential of change in the 100 year storage factors (Table 11). We used the most recent available data (2006 data) on timber products consumption in major end uses in the United States from the latest publication (McKeever, 2009) to construct a new table of 100 year storage factors. It's important to realize that these storage factors are based on the timber usage in a singular year. Ideally, the 100 year storage factors for a particular year's harvest would be calculated using reference data appropriate to that year.

	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels	Misc	Paper
Old K=2 Distribution	0.469	0.229	0.489	0.610	0.363	0.147	0.058
Updated k=2 Distribution	0.462	0.219	0.431	0.571	0.367	0.147	0.058
Old Chi-Squared Distribution	0.509	0.215	0.529	0.697	0.359	0.130	0.058
Updated Chi-Squared Distribution	0.500	0.217	0.444	0.650	0.380	0.130	0.058
Old Standard Gamma	0.512	0.213	0.532	0.705	0.358	0.127	0.058
Updated Standard Gamma	0.503	0.215	0.445	0.656	0.380	0.127	0.058

Table 16: 100 year storage factors as a result of using 2006 timber use data. (McKeever, 2009)

Permanence and the 100 Year Storage Factor

In this paper, we have outlined the calculations for the 100 year storage factor. These calculations signify certain assumptions about the time-value placed on sequestered carbon. Based on way that the CA ARB calculates the 100 year storage factors, both of these hypothetical projects, project Red and project Blue, in Figure 8 will receive the same amount of credits for their project, and are seen as having the same amount of permanent storage. Although they are storing very different amounts of carbon at the end of the 100 year period, they do have the same average storage over this time period. Table 18 below shows how the overall 100 year storage factors would change for each distribution if we were to measure the carbon remaining after 100 years, and not the overall average carbon storage per year.

If the calculations for the 100 year storage factors were based on the amount of carbon remaining after 100 years, the following values in Table 18 below would be used.

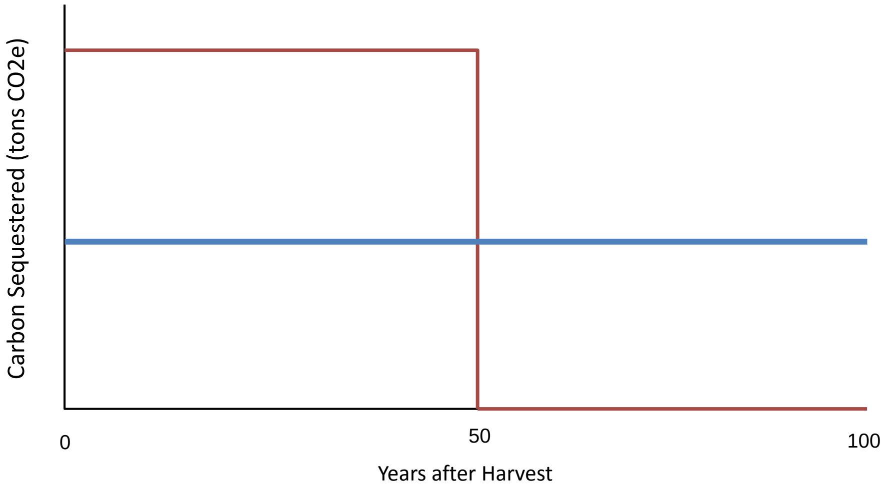


Figure 8: Two hypothetical projects, Red and Blue, with equal amounts of tCO_2e "permanently" sequestered.

	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non Structural Panels
Exponential Distribution	0.234	0.064	0.245	0.349	0.138
K=2 Distribution	0.462	0.219	0.431	0.571	0.367
Chi-Squared Distribution	0.167	0.020	0.168	0.290	0.066
Standard Gamma	0.166	0.020	0.167	0.290	0.065

Table 17: The fraction remaining after 100 years for each product class

Conclusion and Discussion

In investigating the methods used in the CA ARB protocol for measure carbon storage, it is clear that the calculations are sensitive to many things, particularly the wood product class distribution within a harvest and the half lives of the wood products within these classes. As a result, changes in wood product use and product half-lives should be carefully documented and incorporated into future protocol updates. In addition, landfill storage is a significant source of carbon stock, and provides a means of sequestration that is not currently being accounted for consistently in the protocol. Finally, a change to an alternative model for wood product decay could improve accounting accuracy without much difficulty. This change could remove the extreme assumptions implied by the use of the exponential distribution, and provide more reasonable estimates until more data points are made available, allowing for the use of the gamma distribution without simplification.

As we make efforts to decrease the amount of CO_2 in the atmosphere, we will need to rely on many modes of sequestration. Transparent and accurate accounting of the carbon in harvested wood products can help to guide wise decision making in the process.

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Appendix A

	Exponential Distribution	K=2 Distribution	Chi-Squared Distribution	Standard Gamma Distribution
6 year	0.091	0.076	0.071	0.068
12 year	0.177	0.147	0.131	0.127
30 year	0.391	0.354	0.309	0.305
67 year	0.624	0.651	0.675	0.672
70 year	0.635	0.667	0.704	0.701
100 year	0.722	0.782	0.945	0.960

Table 18: The 100 year storage factors for various half-lives

Appendix B

R code for calculating the 100 year storage factor for a distribution, given k and θ values appropriate to the half life. We assume x_0= 1

```
p<-0
for (i in 1:101){
  k=70.333
  h=1
  p[1]<-0
  p[i+1]<-p[i]+1
  g<-function(x) {((x^(k-1))*(exp(1)^(-x/h)))/(gamma(k)*(h^k))}
  decay[i]<-integrate(g, lower=0, upper=p[i])$value
  fr[i]<-(1-decay[i])
}
fr
mean(fr)


#Calculating the 100 year average for each wood product class based on distributions. Again, assumin
#Matrix of wood product class proportions
```

```
#Each colomn represents a wood product type, and the proportion of half life value within it.

#rows go in increasing order of 1/2 lifes [6,12,30,67,70,100]

WP= matrix(

  c(0.058, 0.469, 0.051, 0.002, 0.006,

    0.207, 0.229, 0.181, 0.195, 0.426,

    0.317, 0.187, 0.421, 0.169, 0.296,

    0.055, 0.042, 0.130, 0.067, 0.062,

    0.030, 0.006, 0.022, 0.034, 0.024,

    0.331, 0.067, 0.194, 0.533, 0.186),

  nrow= 6,

  ncol=5,

  byrow=TRUE)

#1/2 life 100 year storage averages [6,12,30,67,70,100] for exponential distribution

#finding the average half life for each wood product class

hl<-c(6,12,30,67,70,100)

halfls<-c(hl%*%WP)

halfls

e<-c(0.090738097, 0.1767409, 0.391461522, 0.623576,0.6351771,0.721604205)

Storagefactors<-c(e%*%WP)

Storagefactors

chi<-c(0.070821051, 0.1306931, 0.30855443, 0.6746007,0.7039981,0.944897391)

chi.storagefactors<-chi%*%WP

chi.storagefactors

g<-c(0.067623766,0.1272277,0.305272264,0.6715991,0.7012986,0.959620214)

gamma.storagefactors<-g%*%WP

gamma.storagefactors
```