Carbon Sequestration Due to Commercial Forestry: An Equilibrium Analysis

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Abstract

Carbon sequestration is one of the tools being used to respond to climate change risks. It is known that carbon stored in wood products is a type of sequestration. However, time frames for evaluating wood use can affect conclusions about sequestration benefits; a long-term perspective and large spatial scale may help clarify these issues. Therefore, I undertook an equilibrium analysis of ongoing commercial forestry operations, relative to carbon sequestration, at the landscape scale. I found that for simple exponential decay functions for wood remaining in use over time, the total sequestered wood at equilibrium is simply the integral of the decay function multiplied by wood product produced. I show that this simple multiplier is a linear function of half-life. For a 50-year wood half-life, this equilibrium multiplier is 72.1. The half-life depends on the specific wood product (lumber, etc.). For waste wood used for energy at mills, typical values yielded a 100-year sequestration (avoided emissions) value of $12H$ where H is tons of carbon in logs delivered to the mill. This exercise demonstrates that commercial forestry is a significant provider of carbon sequestration through wood products, in addition to other sequestration benefits. The simple multipliers developed here are intuitive and can be easily used with operational wood product data at any scale.

Concern about climate change impacts has led to a search for ways to reduce fossil fuel emissions and to sequester carbon. In addition to technologies to sequester carbon from power plant emissions, all of which are still experimental, attention has been focused on human land use. Griscom et al. (2017) showed that major sequestration gains are possible by reforestation, reducing deforestation, altered agricultural practices, and other activities. Many studies have looked at various aspects of wood use (e.g., Skog 2008, Asante and Armstrong 2012, Oliver et al. 2014), but some misconceptions about forest growth and commercial forest operations are common (Prisley et al. 2018). For example, the short-term pattern of carbon emissions following harvest of a single stand may be evaluated, whereas forestry is an ongoing process (Prisley et al. 2018). My analysis here is intended to demonstrate how simple models in an equilibrium framework can help clarify the role of commercial forestry in achieving sequestration goals, specifically related to producing wood products.

Methods

To estimate future sequestration, it is necessary to use a scenario approach, as future human activities relative to wood use are not predictable in any detail. In this analysis, I considered an ongoing forest management scenario on commercially managed forestlands. That is, I did not start with unmanaged forest as in Sterman et al. (2018). In a managed landscape using even-aged forest management, a stand grows until its economic rotation age, at which point the stand is harvested and replanted. Land use is assumed static (remains forested) and annual harvest is assumed to be the same each year (emulates sustainable management). Thus, carbon in the forest per se is at equilibrium (Prisley et al. 2018) because harvest equals growth. I consider both paper and solid wood products in what follows. In uneven-aged management, wood is periodically removed from a stand without stand replacement. The logic here is the same as for even-aged management, with a stable forest carbon base over time. The even-aged case is modeled here for simplicity.

A forest products mill, such as a paper mill, is generally a large-scale, ongoing operation that uses wood every year. Many mills have been in operation for over 70 years, and although there is variance around demand for products, as a long-term average, we can model this as a steady-state operation. The land base that provides raw materials to a

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mill (procurement area or wood basket) will ideally contain forest stands in all age classes up to harvest age (referred to as a regulated forest). In the case of a 22-year rotation age (e.g., in the US South), 1/22 (4.5%) of the land will be in age 1, age 2, etc., to age 22. This number will vary for different forest products (e.g., pulp wood, sawtimber, etc.) and for different regions due to variable regional growth rates. In practice, such a distribution is the goal of management and is rarely perfectly achieved (e.g., changing markets, presence of nonharvested areas within a wood basket, forest practices rules or forest certification standards, etc.), but by assuming such an ideal distribution, certain computations are simplified. Because all stands are growing each year, the harvest of the mature stand (age 22) is exactly balanced by growth in other stands, yielding a zero net forest carbon change over time (Prisley et al. 2018). There are, of course, historical changes in land use and wood consumption that can be considered, but my goal here is to simplify the analysis by focusing on consequences of long-term processes. My concern is thus with the fate of harvested wood in terms of sequestration. I do not consider counterfactuals, such as returning commercial forest to wilderness, nor do I consider transients such as those due to changing demand for wood (e.g., for bioenergy).

It is standard practice to use exponential decay functions for wood following harvest to track how much remains sequestered after *n* years (Smith et al. 2006, Skog 2008). Carbon in wood products is returned to the atmosphere via multiple paths. Wood that is in products may be disposed of when no longer needed and burned or landfilled. Wood products may suffer rot and decay. Wood/paper in landfills decays, but slowly. Using historical data on the mix of wood products, it is then possible to compute inventories of wood still sequestered (e.g., Skog 2008) or to compute sequestration under future scenarios (e.g., Nepal et al. 2012). Such computations reveal that sequestered wood due to past harvests is continuing to increase (e.g., Skog 2008, US Environmental Protection Agency 2019) because decay (loss) of wood from products is slow. The fact that wood in use is lost according to an exponential decay function means that if there is a steady-state (constant) harvest level, then eventually the rate of loss to the atmosphere will equal the harvest rate, and an equilibrium will exist. The two conditions of constant forest carbon in a managed forest and harvest equal to decay allow us to perform an equilibrium analysis. This is an idealized scenario that clarifies sequestration benefits of commercial forestry. In this long-term context, some simple rules of thumb can be developed that can be applied to any scale of harvesting (a mill, a company, a state). The developed indices will be approximate, but useful. In particular, the indices developed can be applied to the long term (e.g., the year 2100) rather than just historical data as per Skog (2008), for example.

Results

We can divide harvested wood into four main pools, though finer divisions are possible: harvest residuals; paper products; wood products; and mill waste. Harvest residuals are branches, nonmerchantable trees, and so on. I do not consider a scenario that includes use of residuals (e.g., tops) as this is not a standard practice. At a mill, waste products remove roughly 43 percent of carbon from woody material with a little over half of that being burned for energy (Smith et al. 2006, table 6 for wood products). The remainder goes into paper products. Some paper products are used quickly and decompose (e.g., toilet paper), while others are in circulation longer, may be recycled, and may then decompose slowly in a landfill. I assume for the moment that paper products have a 4-year half-life (2-yr half-life in products plus incomplete decay in landfills; Skog 2008). At any given time, the amount of paper products (in carbon units) remaining out of the atmosphere is the amount just harvested (*H*) plus the amount remaining from all previous harvests. Using the decay curve

$$S_t = Pe^{-\alpha t} \tag{1}$$

for the fate of a unit of wood *P* (actually made into paper) at time *t*, where $P = L \times H$ (losses due to processing [*L*] times logs harvested [*H*]), where *P* (in carbon units) is product per year (assumed constant by the equilibrium condition), *S* is sequestered carbon, and α is the decay rate. The amount remaining in product at the present time is the current production, plus the amount not decayed from the previous year, plus the amount not decayed from 2 years ago, etc., is the following:

$$S = Pe^{0} + Pe^{-\alpha} + Pe^{-2\alpha} + \ldots \tag{2}$$

or, in integral form:

$$S = P\int_{t=0}^{\infty} e^{-\alpha t} \tag{3}$$

Because the curves go to zero by a few years for paper, it does not take long for equilibrium to be achieved. For the infinite (equilibrium) integral, the solution to Equation 3 is

$$S = P\left(\frac{1}{-\alpha}e^{-\alpha\infty} - \frac{1}{-\alpha}e^{-\alpha\cdot 0}\right) \tag{4}$$

The first exponential term goes to zero and the second to one and negatives cancel, leaving

$$S = P/\alpha \tag{5}$$

For a 4-year half-life, $\alpha = 0.17329$ and $S = 5.77P$; if we consider mill operations over 100 years (a 100-yr look-back), we can use the equilibrium result for paper products (Eq. 5) because equilibrium will have been achieved by this time. This *S* value is the total carbon going into paper products after subtracting residues and manufacturing losses from the amount harvested. The multiplier for any given *P* (e.g., company-scale, state, region) is simply 1/α.

For solid wood products, we can assume roughly a 50-year half-life (Miner 2006). This is an approximate, conservative value, with wood in homes having a 78-year half-life (Skog 2008) but other wood uses (temporary construction lumber, pallets) a much shorter life. This does not capture residence time in landfills and is just for illustration. In this case, $\alpha = 0.0138629$ and the multiplier is 72.1. For such a long half-life, equilibrium takes a while to be reached. In this case the 100-year look-back multiplier is 54.1 and the 200-year look-back (from the year 2100, for example) is 67.6. A long look-back makes sense because society has been utilizing wood for a long time. Because various wood products have different half-lives, it is useful to illustrate the full range of values. For half-lives from 1 to 70, the equilibrium multiplier *M* is simply a straight line

(Fig. 1) with the following equation:

$$M = \frac{HL}{-\text{Ln}(0.5)} \tag{6}$$

where HL is half-life in years. For more complex decay functions (e.g., Miner 2006) the integral can be found numerically.

A more detailed analysis can consider multiple wood use categories (lumber, plywood, construction wood). Taking as an example the northeastern US softwood lumber case of Smith et al. (2006, their table 6), the time curve (Fig. 2) can be summarized by a two-part exponential with fast (10.8-yr half-life) and slow (273.8-yr half-life) components due to the incomplete decay of wood in landfills and the long use life of wood in structures. The curve fitted to the Smith et al. (2006) data can be extrapolated to longer time frames. For this case, the 100-year look-back multiplier (for actual wood products, not logs) is 38.3, the 200-year look-back is 66.1, and the equilibrium is 162.7.

Waste at a paper mill is typically burned to produce steam and electricity. A unit of burned-wood carbon offsets about 0.5 units of fossil-fuel carbon (Oliver et al. 2014), essentially keeping it in the ground (avoided emissions). As this occurs every year (is not a steady-state value), the sequestration (avoided emission) accumulates over time. For a unit of residual waste carbon burned for energy, R, the fossil fuel break-even point is just 2 years because we are not comparing it to leaving the forest to grow. Put in terms of H, logs leaving the forest, with E percent burned for power at the mill ($0.24H$ for softwood sawlogs from Smith et al. 2006, table 6), the 100-year look-back is this:

$$R = 0.5 \times E \times H \times 100 \tag{7}$$

For E from sawlogs (0.24), it is

$$R = 12H \tag{8}$$

and the 200-year look-back is twice this. This means that over the long term, waste use for energy has a nontrivial impact, as also noted by Oliver et al. (2014) for a single-year analysis. Oliver et al. (2014) showed that substitution of wood for steel and concrete has further CO_2 benefits in the context of ongoing economic activity.

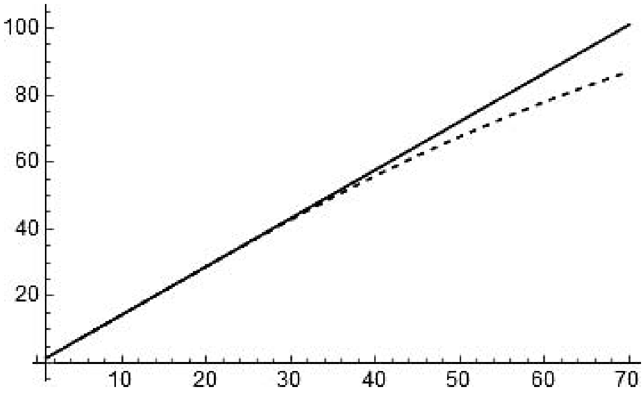

Figure 1.—Carbon sequestration multiplier as a function of half-life. Solid line: equilibrium value. Dashed line: 200-year look-back. This would be multiplied times the wood product produced rather than logs leaving the woods.

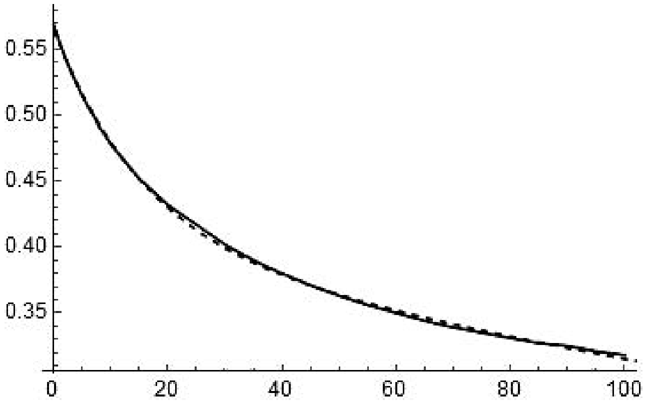

Figure 2.—Percentage of softwood sawlogs remaining sequestered with time (from Smith et al. 2006, table 6). Best fit line (dashed) is a double exponential. The intercept is the percentage of wood not lost during processing (e.g., bark).

Discussion

The equilibrium approach used here provides a more intuitive view of the sequestration question. The simple multiplier of P based on the half-life (Eq. 6) can be easily scaled to any size of land base. For more complex decay functions (e.g., Fig. 2), numerical look-back calculations are simple. These simple multipliers are for the steady-state (equilibrium) condition of stable harvests and are thus approximate rather than precise as constant land use and wood harvest levels never hold perfectly. However, they can be directly related to annual harvests in a simple way. If wood in landfills decays more slowly than past studies assume, these multipliers will underestimate sequestration. Because the multipliers are on a per-unit harvested wood basis, increases in wood use in the future do not affect the multiplier values for current harvests.

Studies based on an initially uncut land base or looking forward from a mature stand (e.g., Gutrich and Howarth 2007, Nunery and Keeton 2010, Asante and Armstrong 2012, Ter-Mikaelian et al. 2015, Sterman et al. 2018) will necessarily draw more pessimistic conclusions about sequestration due to forestry than landscape-based analyses (Cherubini et al. 2013, Prisley et al. 2018) because the vast majority of commercial forestry is practiced on a managed landscape, not within old-growth forest stands. I believe an equilibrium (or long-term) analysis based on ongoing commercial forestry more closely matches the real-world situation because commercial wood use is an old and ongoing process.

For bioenergy, using manufacturing waste, a standard practice in the wood products industry (Smith et al. 2006, Oliver et al. 2014), has a large fossil-fuel displacement value which is equivalent to sequestration (Oliver et al. 2014; this study). For the case of beginning to use logs for energy (a transient), there will be a debt for a period roughly equal to two timber rotations due to the displacement rate of wood for coal. The benefit will depend a great deal on what types of wood are used for energy and other assumptions (Lamers and Junginger 2013, Chen et al. 2018). This analysis does not address these complexities.

Price or payment incentives to store carbon have been shown to increase rotation length, which reduces harvests, or prevents them in the price limit (Spring et al. 2005, Keleş and Başkent 2007, Vass and Elofsson 2016). Van Minnen et al. (2008) noted that real-world constraints may limit land available for sequestration projects, perhaps making long-rotation forestry not economically feasible (Hedenus and Azar 2009). In addition, leakage (wood harvests outside the regulated area) is likely if demand is not reduced (e.g., Murray et al. 2003). The analysis performed here suggests that in the long term, commercial forestry makes a substantial contribution to sequestration while also providing jobs, products, and ecosystem services.

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