Greenhouse Gas Impacts of Forest Management: an Annotated Source List

Prepared by Colleen Ryan, 3/4/2022

Note: where quoted materials are bolded, the emphasis is mine.

Contents:

1. Comprehensive GHG Impacts of Forest Management/Harvesting

Bellassen, V. and S. Luyssaert. 2014. Carbon sequestration: Managing forests in uncertain times. *Nature* 506, 153–155. https://doi.org/10.1038/506153a

Because the future behavior of the forest carbon sink given climate change is not well understood, the authors recommend prioritizing management strategies "that **increase both the amount of wood produced and the carbon stock retained in the forest.**" (as EF will do in the Acadian Forest)

Cameron, R. E., Hennigar, C. R., MacLean, D. A., Adams, G. W., & Erdle, T. A. 2013. A comprehensive greenhouse gas balance for a forest company operating in northeast North America. *Journal of Forestry*, 111(3), 194–205. https://doi.org/10.5849/jof.12-043

This study projected GHG impacts of forest management and wood products produced on Irving lands in ME, NB, and NS over 100 years. Based on current management, mill operations, and electricity supply mixes, operations would be a net carbon source over 100 years (excluding substitution effects). If pulpwood were diverted to energy production, this would change to a net sink (69.3 t CO_2e/ha of potential GHG offsets over 100 years). A no-harvest scenario would produce 168.3 t CO_2e/ha of potential GHG offsets over 100 years. Applying a substitution factor of 2.1 (from Sathre and O'Connor) would reduce the net sink from the unharvested forest to 71.5 t CO_2e/ha. However, the authors note that the risk of additional emissions from disturbances, particularly spruce budworm, would be higher in the unmanaged forest, and thus managed forest could have a net GHG effect similar to unmanaged forest: "Our results suggest that depending on factors such as disturbance risk, products produced, and grid electricity emissions, **intensive forest management to produce a sustainable longterm supply of solidwood products and biofuel may result in a GHG mitigation potential similar to that when forests are allowed to grow unmanaged, while providing forest products that produce societal benefits**." Note that this study did not consider leakage, which, if included, would substantially reduce the net carbon sink from the no management scenario.

Ganguly, Indroneil, Francesca Pierobon, and Edie Sonne Hall. 2020. "Global Warming Mitigating Role of Wood Products from Washington State's Private Forests." ***Forests*** **11, no. 2: 194. https://doi.org/10.3390/f11020194.**

This study looked at the fate of carbon from private forests in Washington state over 100-year period, assuming current harvest levels and product mixes continue. Found that "after factoring in the greenhouse gas emissions associated with the harvest operations and wood products manufacturing processes, within the temporal model, the results show a net beneficial impact of approximately 1.7 million tCO_2eq, on an annual basis." That is, products from these forests store 1.7 million tCO_2eq per year, on top of carbon accumulation in the forest, which is estimated at 7.4 million tCO_{2eq} per year.

Note: this study did not include substitution effects, landfilled wood products, or any possibility of recycling wood products. It assumed carbon neutrality of biogenic carbon (because net growth inclusive of fires and other disturbances exceeds harvest for Washington's private forests as a whole). Thus, it can't be used to directly compare the impacts of current management with alternative scenarios, including proforestation. However, it does indicate that current practices on private forest land are sequestering more than 2 tCO_2eq per hectare per year.

Hennigar, Chris, David MacLean, and Luke Amos-Binks. 2008. "A novel approach to optimize management strategies for carbon stored in both forests and wood products." ***Forest Ecology and Management*** **256: 786-797. 10.1016/j.foreco.2008.05.037.**

The authors modeled a hypothetical forest in New Brunswick, and estimated that **optimizing forest management for carbon storage in both the forest and harvested wood products combined stored more carbon over a 250-year period than optimizing for in-forest carbon storage alone,** while allowing for much higher harvest levels that could make this management option more economically feasible. Their model assumed that 50% of the carbon in landfilled wood products was degradable and would degrade at a rate of 1% per year. In situ measurements of landfilled wood products, such as those by Ximenes et al. (2008 and 2018), and Wang et al. (2013), suggest that the actual proportion of landfill-degradable carbon in wood products is much lower. Using a lower number would mean that optimizing for carbon storage in wood products and the forest combined would potentially lead to substantially higher total carbon storage than optimizing for in-forest carbon alone.

IPCC, 2019. Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

Section B.5:

"B.5.3 Reducing deforestation and forest degradation lowers GHG emissions (high confidence), with an estimated technical mitigation potential of 0.4–5.8 $GtCO_2\ yr^{-1}$. By providing long-term livelihoods for communities, sustainable forest management can reduce the extent of forest conversion to non-forest uses (e.g., cropland or settlements) (high confidence). **Sustainable forest management aimed at providing timber, fibre, biomass, non-timber resources and other ecosystem functions and services, can lower GHG emissions and can contribute to adaptation (high confidence).**"

"B.5.4 **Sustainable forest management can maintain or enhance forest carbon stocks, and can maintain forest carbon sinks, including by transferring carbon to wood products, thus addressing the issue of sink saturation (high confidence). Where wood carbon is transferred to harvested wood products, these can store carbon over the long-term and can substitute for emissions-intensive materials reducing emissions in other sectors (high confidence). Where biomass is used for energy, e.g., as a mitigation strategy, the carbon is released back into the atmosphere more quickly (high confidence).**"

Keith, H. et al. 2014: Managing temperate forests for carbon storage: Impacts of logging versus forest protection on carbon stocks. Ecosphere, 5 (6): 1-34. doi:10.1890/ES14-00051.1.

In an Australian mountain ash forest where only 4% of pre-harvest biomass was converted to sawn timber products with lifetimes of 30–90 years, a no-harvest scenario was better at reducing GHG emissions than harvesting, when carbon in the forest and in products was considered (but not substitution). The authors conclude that "the mitigation value of forest management options of protection versus logging should be assessed in terms of the amount, longevity and resilience of the carbon stored in the forest, rather than the annual rate of carbon uptake."

Kurz, W.A., C. Smyth, and T. Lemprière, 2016: Climate change mitigation through forest sector activities: Principles, potential and priorities. Unasylva, 67, 61–67.

This paper sets forth principles for accurately assessing impacts of forest management on climate change mitigation, including the need to account for all carbon impacts in the forest and in the economy, and the importance of comparing proposed activities to a business-as-usual baseline. It points out how failing to account for some types of effects can lead to poor policy, such as how the exclusion of wood products from IPCC accounting guidelines removed incentives to maintain carbon storage in harvested wood products.

Lippke, Bruce; Gustafson, Richard; Venditti, Richard; Steele, Philip; Volk, Timothy A.; Oneil, Elaine; Johnson, Leonard; Puettmann, Maureen E.; Skog, Kenneth. 2012. Comparing life-cycle carbon and energy impacts for biofuel, wood product, and forest management. Forest Products Journal 62(4): 247–257.

In PNW forests on a 45-year rotation, "the sum of the carbon in products and the forest can be less than a no-action alternative of not harvesting for a period of time. But that leaves out the substitution of wood replacing nonwood. The impact of wood products substituting for nonwood products more than offsets the shortfall in product carbon relative to the no-harvest alternative immediately." (This assumes an average substitution factor around 2, per Sathre and O'Connor 2010.) The authors also note that the PNW has the highest ratio of long-lived wood products per volume of harvested wood in the US.

"It is important to note that the sustainability of reducing carbon emissions or fossil fuel imports flows directly from using wood to displace fossil fuel–intensive products and fuels, forest rotation after rotation. Carbon stored in the forest or wood products may offset fossil fuel carbon emissions for a period of time but do not displace them. Carbon stores can only be increased by using the harvest to produce items that store carbon**. Increasing carbon stores in existing forests that could otherwise be used for products or biofuels ultimately reduces opportunities to displace fossil fuel emissions."**

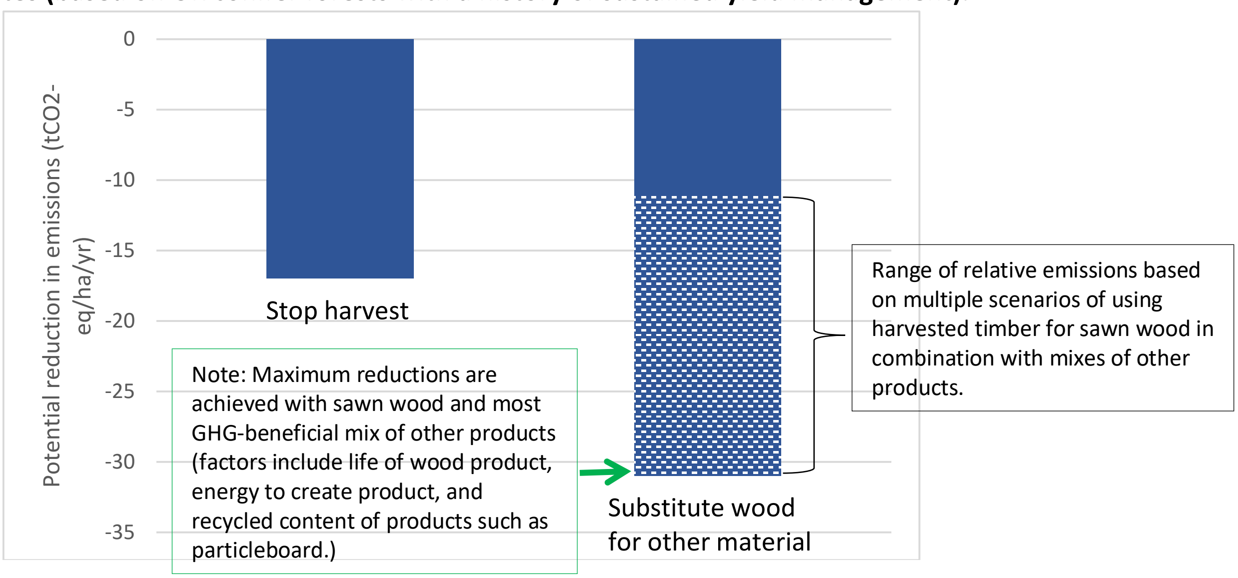
Lundmark, T. et al. 2014: Potential roles of Swedish forestry in the context of climate change mitigation. Forests, 5, 557–578, doi:10.3390/f5040557.

This study modeled the Swedish forest industry, assuming that harvest = growth, in line with Swedish forest policy. Found that "the average CO_2 emissions reduction effect in a managed forest is on the order of 500 kg CO_2 m^{-3} of harvested biomass use." But, "(s)ince one cubic meter of biomass contains carbon corresponding to 700–900 kg CO_2, depending on the wood density, increasing the standing volume of the forest would be a more efficient measure to mitigate climate change as long as the standing volume of the forest can continue to increase. Focusing solely on increasing carbon stocks in this way is, however, a limited climate mitigation strategy, since it is not possible to store unlimited quantities of carbon in the forest. If this method were to be applied, timber reserves in Sweden would initially increase, but would eventually reach a new equilibrium between growth and natural attrition. When this balance is reached, the —uncultivated forest landscape‖ would, in principle, be CO_2 neutral, i.e., it neither sequesters nor releases carbon to any significant extent. Another effect would be that possibilities for the sustained harvesting of forest biomass for consumption would be eliminated. Consumption must then either decrease or be met with something other than renewable forest products, e.g., more energy-intensive materials, fossil fuels or other energy sources."

Matthews, R., N. Mortimer, E. Mackie, C. Hatto, A. Evans, O. Mwabonje, T. Randle, W. Rolls, M. Sayce, and I. Tubby. 2014. *Carbon impacts of using biomass in bioenergy and other sectors: forests.* DECC project TRN 242/08/2011 Final report: Parts a and b.

This study compared the reduction in GHG emissions between a no-harvest scenario and management alternatives for the production and use of wood products over a 20-year time frame (Matthews, et al. 2014). As shown in Figure 4, this analysis found **that harvesting and using wood products had the potential to sequester up to nearly twice as much carbon per year as a no-harvest scenario.** This study and the projected GHG reduction are especially important because the 20-year projection addresses the time frame for mitigation that is crucial to avert unacceptable levels of climate change.

Figure 4. Relative greenhouse gas emissions over 20 years comparing use of wood to use of non-wood substitutes (based on UK conifer forests with a history of sustained yield management).



Source: NEFF, based on data from Figure 5.12 and Table 5.2 from Matthews (2014).

Oliver, C. D., N. T. Nassar, B. R. Lippke, and J. B. Mccarter. 2014. Carbon, Fossil Fuel, and Biodiversity Mitigation with Wood and Forests. *Journal of Sustainable Forestry* 33 (3): 248–75. https://doi.org/10.1080/10549811.2013.839386.

This global analysis demonstrated the potential to increase climate change mitigation from the world's forests by harvesting more of their "excess growth" (growth that surpasses current harvest). "**More CO_2 can be sequestered synergistically in the products or wood energy and landscape together than in the unharvested landscape**," with the greatest benefits coming from avoided emissions through efficient substitution of wood for concrete and steel.

Olsson, L., H. Barbosa, S. Bhadwal, A. Cowie, K. Delusca, D. Flores-Renteria, K. Hermans, E. Jobbagy, W. Kurz, D. Li, D.J. Sonwa, L. Stringer, 2019: Land Degradation. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van

Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

Section 4.8.4

"With increasing forest age, carbon sinks in forests will diminish until harvest or natural disturbances, such as wildfire, remove biomass carbon or release it to the atmosphere (Seidl et al. 2017). While individual trees can accumulate carbon for centuries (Kohl et al. 2017), stand-level carbon accumulation rates depend on both tree growth and tree mortality rates (Hember et al. 2016; Lewis et al. 2004). SFM, including harvest and forest regeneration, can help maintain active carbon sinks by maintaining a forest age-class distribution that includes a share of young, actively growing stands (Volkova et al. 2018; Nabuurs et al. 2017). The use of the harvested carbon in either long-lived wood products (e.g., for construction), short-lived wood products (e.g., pulp and paper), or biofuels affects the net carbon balance of the forest sector (Lempriere et al. 2013; Matthews et al. 2018). The use of these wood products can further contribute to GHG emission-reduction goals by avoiding the emissions from the products with higher embodied emissions that have been displaced (Nabuurs et al. 2007; Lempriere et al. 2013). In 2007 the IPCC concluded that **'[i]n the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit'** (Nabuurs et al. 2007). The apparent trade-offs between maximising forest carbon stocks and maximising ecosystem carbon sinks are at the origin of ongoing debates about optimum management strategies to achieve negative emissions (Keith et al. 2014; Kurz et al. 2016; Lundmark et al. 2014). SFM, including the intensification of carbon-focused management strategies, can make long-term contributions towards negative emissions if the sustainability of management is assured through appropriate governance, monitoring and enforcement. As specified in the definition of SFM, other criteria such as biodiversity must also be considered when assessing mitigation outcomes (Lecina-Diaz et al. 2018). Moreover, the impacts of changes in management on albedo and other non-GHG factors also need to be considered (Luyssaert et al. 2018) (Chapter 2). The contribution of SFM for negative emissions is strongly affected by the use of the wood products derived from forest harvest and the time horizon over which the carbon balance is assessed. SFM needs to anticipate the impacts of climate change on future tree growth, mortality and disturbances when designing climate change mitigation and adaptation strategies (Valade et al. 2017; Seidl et al. 2017)."

Peckham, Scott D.; Gower, Stith T.; Buongiorno, Joseph. 2012. Estimating the whole-system forest carbon budget and maximizing future carbon uptake. Carbon Balance and Management 2012, 7:6. doi:10.1186/1750-0680-7-6

The authors modeled the carbon budget for a National Forest in WI, including C storage in wood products, but not substitution effects. Found that **increasing** harvest from current levels of about 1% per year would **increase** net carbon uptake. "…we show an optimized harvesting strategy would increase future carbon sequestration, or wood production, by 20-30%, reduce long transportation chain emissions, and maintain many desirable stand structural attributes that are correlated to biodiversity. Our results for this forest region suggest that **increasing harvest over the next 100 years increases the strength of the carbon sink**, and that carbon sequestration and wood production are not conflicting for this particular forest ecosystem."

Smyth, C.E., Stinson, G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G.J. & Kurz, W.A. 2014. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. Biogeosciences 11: 3515–3529.

This study compared impacts of alternative management strategies on the mitigation potential of the whole Canadian forest products industry, including in-forest carbon, carbon in products, and substitution (using relatively low substitution factors of 0.38-0.77). The best effects came from a mix of strategies in different regions of the country, confirming **that the best forest management approach will vary by specific circumstances**. In most regions, mitigation was optimized by maintaining harvest while increasing wood utilization (e.g., recovering some logging slash for bioenergy use) and shifting toward longer-lived wood products, but in some areas mitigation was optimized by reducing harvest while shifting toward longer-lived wood products. Overall, reducing harvest was not as effective as increasing utilization.

Werner, Frank, Ruedi Taverna, Peter Hofer, Esther Thürig, and Edgar Kaufmann. 2010. "National and Global Greenhouse Gas Dynamics of Different Forest Management and Wood Use Scenarios: a Model-Based Assessment." ***Environmental Science & Policy*** **13 (1): 72–85. https://doi.org/10.1016/j.envsci.2009.10.004.**

This study used modeling to assess carbon tradeoffs among different forest management and wood use strategies. Included carbon in the forest and in products, as well as substitution effects and use of wood products for energy production. They found that the contribution of forests to climate change mitigation is maximized when sustainable forest growth is maximized and continuously harvested, with wood products used as long as possible and waste wood burned for energy. **Reducing harvest to store more carbon in the forest is less effective at mitigation than optimal management.**

2. <u>Importance of Using a Systems Approach (including forest carbon and substitution)</u>

Dugan, A. J., Birdsey, R., Mascorro, V. S., Magnan, M., Smyth, C. E., Olguin, M., & Kurz, W. A. 2018. A systems approach to assess climate change mitigation options in landscapes of the United States Forest Sector. Carbon Balance and Management, 13(1). https://doi.org/10.1186/s13021-018-0100-x

> Used modeling to assess alternative approaches to lessening or delaying future reductions in the carbon sink provided by forests over a 32-year period in two case study regions: coastal SC and northern WI. "**This research highlights the importance of taking a systems approach that assesses net emissions from the forest ecosystem, land-use change, HWP, and avoided emissions when evaluating forest sector climate change mitigation scenarios across large, multiownership landscapes.**" "Maintaining forests as forests, extending rotations, and shifting commodities to longer-lived products had the strongest mitigation benefits over several decades." Note: this study did not address leakage.

Lemprière, T.C.; Kurz, W.A.; Hogg, E.H.; Schmoll, C.; Rampley, G.J.; Yemshanov, D.; McKenney, D.W.; Gilsenan, R.; Beatch, A.; Blain, D.; Bhatti, J.S.; Krcmar, E. 2013. Canadian boreal forests and climate change mitigation. Environmental Reviews 21(4):293-321.

> Synthesized the literature on the mitigation potential of Canada's boreal forests. Found that **assessments of GHG mitigation effects of forest management must use a systems approach and "must take into account the impact of activities on carbon storage in both forests and harvested wood products, and also account for the greenhouse gas impacts of using wood instead of fossil fuels or alternative products like concrete and metals."** "The greatest short-run boreal mitigation benefit generally would be achieved by avoiding greenhouse gas emissions; but over the longer run, there could be significant potential in activities that increase carbon removals."

Ter-Mikaelian, M.T., S.J. Colombo, and J. Chen, 2014: The burning question: Does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. J. For., 113, 57–68, doi:10.5849/jof.14-016.

> Reviewed the pitfalls of using some common assumptions in forest carbon accounting (specifically with respect to bioenergy), including failing to include changes in forest carbon stocks in the no-harvest alternative and assuming that wood from sustainably harvested forests is carbon neutral. Notes that harvesting live trees for bioenergy typically takes many decades to realize a GHG benefit, but that the timeframe varies widely depending on the characteristics of the forest and the energy source being replaced.

3. Leakage/Demand for Materials

Berlik, M. M., D. B. Kittredge, and D. R. Foster. 2002. The illusion of preservation: a global environmental argument for the local production of natural resources. *Journal of Biogeography*, 29:1557-1568.

> **Argued that conservation of natural resources in affluent countries often leads to greater environmental harms as resource extraction is shifted to places where the impacts are greater and regulatory oversight is often weaker**, with Massachusetts wood consumption as an example. "When aggressive reductions in wood consumption and effective recycling are combined with judiciously increased harvest levels, 50% of Massachusetts's wood consumption could be met at sustainable rates, even while preserving large undisturbed blocks of forest." "Forestry and the sustainable generation of wood in Massachusetts would allow preservation of primary forests elsewhere in the world."

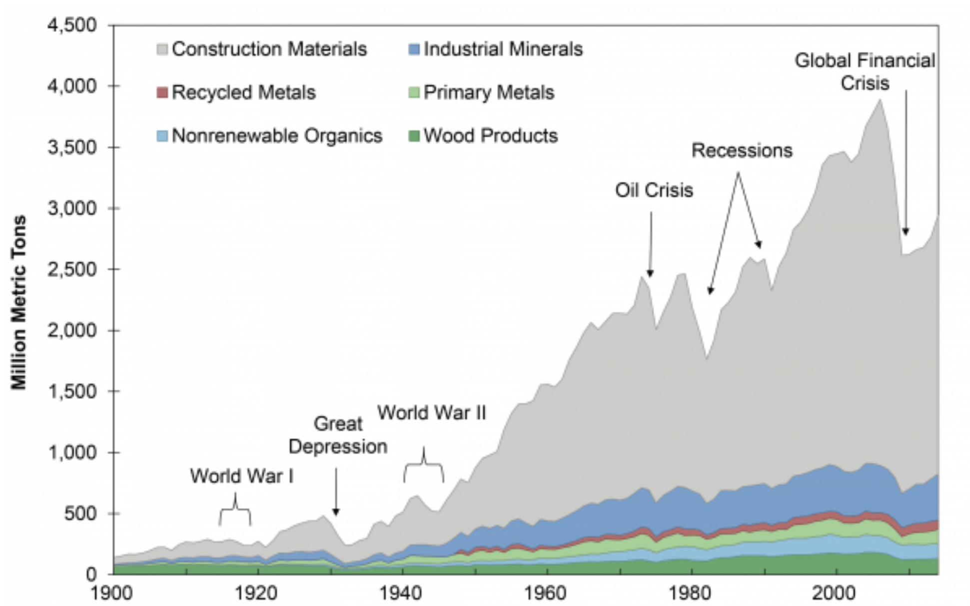
Gan, Jianbang and Bruce McCarl. 2007. "Measuring transnational leakage of forest conservation." *Ecological Economics* 64(2): 423-432. https://doi.org/10.1016/j.ecolecon.2007.02.032.

> "We estimate that a significant portion (42%–95%) of the reduced forestry production implemented in a country/region can be transferred to elsewhere, offsetting environmental gains." This study modeled the effects of reduced harvests due to forest conservation in one country on harvest levels in other countries. In all countries but one, at least 65% of production was leaked to other countries. They also found that "a significant portion of the reduced forestry production in developed countries implementing conservation would be transferred to developing countries where forest conservation is often argued to be critically needed."

Matos, G. 2017. Use of raw materials in the United States from 1900 through 2014: U.S. Geological Survey (USGS) Fact Sheet 2017–3062, 6 p. https://pubs.usgs.gov/fs/2017/3062/fs20173062.pdf

Shows ongoing growth in demand for raw materials over time. Note that this graph is by weight, so does not illustrate the relative environmental or climate impacts of materials. "Construction materials" here includes sand, gravel and crushed stone. "Nonrenewable organics" means petroleum products.

Figure 1. U.S. nonfuel material consumption, 1900-2014



[1]

Source: Matos 2017

Murray, B.C., B.A. McCarl, and H.-C. Lee. 2004. Estimating leakage from forest carbon sequestration programs. Land Economics 80 (1):109-124.

Found leakage from forest carbon sequestration programs in the U.S. can range from 10% to 90%.

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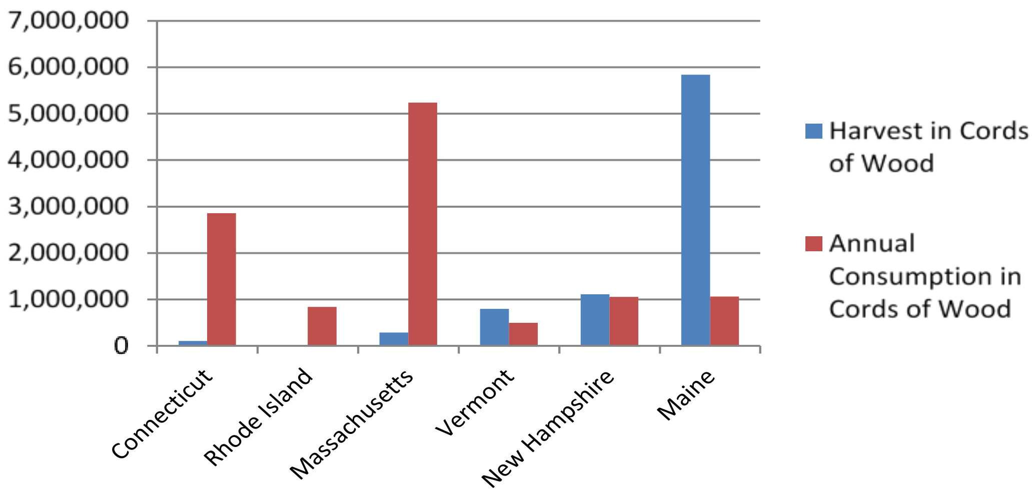
[1] This graph shows raw materials only, measured by weight. "Construction materials" includes sand, gravel, and crushed stone (including those used to make concrete). "Wood products" includes all forest products. "Nonrenewable organics" includes all fossil fuels used for any purpose.

Ten Broeck, C. 2014. Grow as Much as We Use, *in New England Forests: The Path to Sustainability, Technical Reports*, edited by R. A. Giffen. New England Forestry Foundation, Littleton, MA.

Compares current growth and harvest of wood in New England to current consumption.

Figure 9. State annual harvest and consumption of cords of wood



Source: Ten Broeck (2014)

Uri, N. D. and R. Boyd. 1990. Considerations on modeling the market for softwood lumber in the United States, *Forest Science* 36 (3) (1990) 680–692.

Found that there is a national market for softwood lumber in the U.S. (i.e., reducing harvest in one location will affect prices and lead to increased production in other locations).

Wear, D. N., and B. C. Murray. 2004. Federal Timber Restrictions, Interregional Spillovers, and the Impact on US Softwood Markets. *Journal of Environmental Economics and Management* 47 (2): 307–330. https://doi.org/10.1016/s0095-0696(03)00081-0.

Looked at the US softwood market following reductions in timber sales in the western U.S. beginning in the late 1980s**.** Found that **84% of the harvest reductions on public lands in the West were leaked to private lands in the West and to other parts of North America (the South and Canada). "**The findings here demonstrate one recurring theme in natural resource policy: **resource restrictions in one place tend to move extractive activity to other places…"**
"…measures to protect habitat in the western US may have caused a degradation of habitat and other ecological services provided by forests in other places."

4. Substitution Factors

Bergman, R.; Puettmann, M.; Taylor, A.; Skog, K. E. 2014. The Carbon Impacts of Wood Products. *Forest Prod. J.* Volume 64, Number 7/8, 2014; pp. 220–231.

Compiled substitution factors for a variety of wood products (mostly construction materials) sourced from the U.S., some with specific regional sources indicated. All calculated factors were positive, indicating that using wood products reduces GHG emissions. Factors varied from 0.8 to 3.3, including these Northeast-specific values: 2.5 for hardwood lumber replacing PVC moulding; 2.1 for softwood lumber replacing steel studs.

Leskinen, P., G. Cardellini, S. González-García, E. Hurmekoski, R. Sathre, J. Seppälä, C. Smyth, T. Stern, and P. J. Verkerk. 2018. Substitution effects of wood-based products in climate change mitigation. *From Science to Policy* 7. European Forest Institute.

The most comprehensive review of the topic to date, it included 433 substitution factors from 51 international studies encompassing a wide range of geographies, products, assumptions, and methodologies, many of which are not applicable to our region. The **average factor was 1.2**, but specific substitution factors reported varied widely depending on the specific products compared, with 95% of reported values falling between -0.7 and 5.1. (Positive numbers represent kg of C emissions avoided per kg of C in the wood product in use; while negative numbers indicate that the wood product is worse for the climate than the non-wood alternative.)

Sathre, R., and J. O'Connor, J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental science & policy*, 13(2), 104-114.

This review of 21 international studies found an average substitution factor of 2.1, with a range of -2.3 to 15.

5. In-forest Carbon

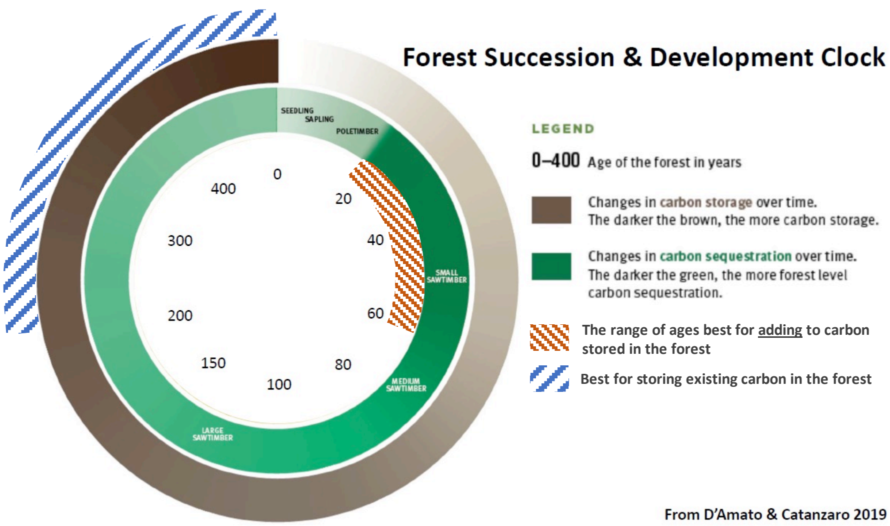
Note: The literature on how in-forest carbon changes over time and in response to management is enormous. This is a sampling of papers, most of which have been cited in one or more NEFF publications. I did not attempt to summarize every study.

Campbell, C., Seiler, J., Wiseman, P., Strahm, B., & Munsell, J. (2014). Soil Carbon Dynamics in residential lawns converted from Appalachian mixed oak stands. Forests, 5(3), 425–438. https://doi.org/10.3390/f5030425

> "…converting unmanaged Appalachian hardwood forest into managed, turfgrass-dominated residential landscapes may affect C depth distribution, but results in little change in total soil carbon sequestration in the upper 30 cm." (evidence that soil carbon can be excluded from in-forest carbon calculations)

Catanzaro P., and D'Amato A. 2019. *Forest Carbon*. Amherst, MA: University of Massachusetts Amherst. 25 p.

This figure was adapted from Catanzaro and D'Amato (2019) (the red and blue hatching was added by NEFF).



From D'Amato & Catanzaro 2019

Domke, G. M., C. H. Perry, B. F. Walters, C. W. Woodall, M. B. Russell, and J. E. Smith. 2016. Estimating Litter Carbon Stocks on Forest Land in the United States. *Science of The Total Environment* 557-558: 469–78. https://doi.org/10.1016/j.scitotenv.2016.03.090.

Domke, G., C. A. Williams, R. Birdsey, J. Coulston, A. Finzi, C. Gough, B. Haight, J. Hicke, M. Janowiak, B. de Jong, W. A. Kurz, M. Lucash, S. Ogle, M. Olguín-Álvarez, Y. Pan, M. Skutsch, C. Smyth, C. Swanston, P. Templer, D. Wear, and C. W. Woodall. 2018. Chapter 9: Forests. In *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report* [Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 365-398, https://doi.org/10.7930/SOCCR2.2018.Ch9.

EPA. 2017. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. EPA 430-P-17-001. U.S. Environmental Protection Agency, Washington, D.C., 633 pp. https://www.epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf

Gunderson, P., E. E. Thybring, T. Nord-Larsen, L. Vesterdal, K. J. Nadelhoffer, and V. K. Johannsen. 2021. Old-growth forest carbon sinks overestimated. Nature 591 https://doi.org/10.1038/s41586-021-03266-z

> The authors contest the plausibility of the carbon flux estimates in Luyssaert, et al. 2008, based on comparisons with estimates of the total terrestrial carbon budget, comparison of current soil carbon levels with the levels projected by the Luyssaert estimates, N deposition levels being too low to support the estimated level of C sequestration, and concerns that eddy-covariance measurements can underestimate Rh, leading to an overestimate of NEP and carbon sequestration. Their analysis of the same data indicates that old forests (200+ years) sequester 1.6 ± 0.6 Mg C/ha/yr on average (30% less than the Luyssaert, et al estimate).

Hoover, C. M. 2011. Management Impacts on Forest Floor and Soil Organic Carbon in Northern Temperate Forests of the US. *Carbon Balance and Management* 6, no. 1. https://doi.org/10.1186/1750-0680-6-17.

Hoover, C. M., W. B. Leak, and B. G. Keel. 2012. "Benchmark carbon stocks from old-growth forests in northern New England, USA." *Forest Ecology and Management* 266: 108–114.

> Found that carbon stocks in old-growth hardwood stands in northern New England (154 Mt/ha excluding soil; 63 Mt/ha in soil to 20 cm) were not significantly different from carbon stocks in mature (80-120 year-old) hardwood stands. The forest floor carbon pool was twice as big in the old-growth stands, but this was not a significant difference. Also documented carbon stocks for old growth softwood stands (199 Mt/ha excluding soil; 68 Mt/ha in soil to 20 cm).

James, J., D. Page-Dumroese, M. Busse, B. Palik, J. Zhang, B. Eaton, R. Slesak, J. Tirocke, and H. Kwon. Effects of Forest Harvesting and Biomass Removal on Soil Carbon and Nitrogen: Two Complementary Meta-Analyses. 2021. Forest Ecology and Management 485: 118935. https://doi.org/10.1016/j.foreco.2021.118935.

Johnson, Dale W, and Peter S Curtis. 2001. Effects of Forest Management on Soil C and N Storage: Meta Analysis. Forest Ecology and Management 140, no. 2-3 (2001): 227–38. https://doi.org/10.1016/s0378-1127(00)00282-6.

Keeton, W.S. 2018. Source or Sink? Carbon Dynamics in Eastern Old-Growth Forests and Their Role in Climate Change Mitigation in Andrew M. Barton and William S. Keeton, *Ecology and Recovery of Eastern Old-Growth Forests*, DOI 10.5822/ 978-1-61091-891-6_14

> Summarizes state of knowledge on carbon in Eastern old-growth forests. Clear consensus that old-growth can store a lot of carbon, with some studies finding key differences between mature and old-growth stands are in downed wood and possibly soil carbon pools. Some studies support the long-held belief that old growth forests reach a steady state level of carbon storage, in some cases peaking, then declining to a steady state. Others suggest that forests can keep sequestering carbon well past age 200 (or even past age 400). "Not all eastern old-growth forests are net carbon sinks, but many are." Studies that show biomass continues to accumulate longer than models would predict: Keeton et al. 2011; Eisen and Plotkin 2015; Gough et al 2016;

Keeton et al. 2007. Studies that support a biomass peak by age 200 or younger: Halpin and Lorimer 2016 (peak at age 200 in Midwestern N. hardwoods), Fahey et al. 2005 (peak around age 80 at Hubbard Brook, likely due to beech disease and soil calcium depletion). "…mounting evidence strongly supports the idea that **conserving remaining old-growth forests and managing for old-growth characteristics in working forests would have carbon value, comprising part of a holistic forest carbon management approach** (McKinley et al 2011; Ford and Keeton 2017)…. Allowing forest biomass to fully recover in secondary forests on some portion of the northeastern landscape has the potential to increase in situ carbon storage in those stands by a factor of 2.3 to 4.2, depending on site-specific variability (Keeton et al. 2011) …. **while old-growth reference stands suggest an inherent carbon storage capacity within the system, future dynamics are likely to depart from historic baselines as environmental boundary conditions are altered by global change** (Ollinger et al. 2008; Seidl et al. 2008)…. in eastern forests that historically developed multi or uneven-aged structure, silviculture can be used to direct or accelerate the development of stand structural complexity and associated high levels of carbon storage (Keeton 2006; Ford and Keeton 2017)." Many, but not all, studies show that the net GHG impact of more intensively managed forests is worse than less intensively managed forests.

Keeton, W. S., A. A. Whitman, G. C. McGee, and C. F. Goodale. 2011. Late-Successional Biomass Development in Northern Hardwood-Conifer Forests of the Northeastern United States. *Forest Science* 57(6).

Assessed change in aboveground biomass over time for 48 mature and 46 old-growth sites in the Northeast. Biomass was correlated with stand age for all aboveground pools (living trees, standing dead, and downed dead). Conclusions: "aboveground biomass can accumulate very late into succession in northern hardwood-conifer forests, recognizing that early declines are also possible in secondary forests as reported previously." "Although secondary forests may have the potential to more than double their aboveground carbon storage in some cases, there are many factors that will influence future trajectories of biomass development." Recommend an approach that includes reserves aimed at development of old-growth structure and strategies to optimize net carbon storage in actively managed forests.

Luyssaert, S. et al. 2008. Old-growth forests as global carbon sinks. *Nature* 455, 213–215. https://doi.org/10.1038/nature07276

Based on a comprehensive literature review of studies that calculated NEP or NPP and Rh for temperate or boreal forests, they determined that most forests more than 200 years old are carbon sinks, with an average sequestration rate of 2.4+/-0.8 tC/ha/yr. "Old-growth forests accumulate carbon for centuries and contain large quantities of it. We expect, however, that much of this carbon, even soil carbon, will move back to the atmosphere if these forests are disturbed." (See Gunderson et al. 2021 for a different interpretation of the same data.)

Makela, A. and H. T Valentine. 2001. The ratio of NPP to GPP: Evidence of change over the course of Stand Development. *Tree Physiology*, 21(14), 1015–1030. https://doi.org/10.1093/treephys/21.14.1015

Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, et al. 2011. A large and persistent carbon sink in the world's forests. *Science* 333:988–93.

Roxburgh, S. H., S. W. Wood, B. G. Mackey, G. Woldendorp, and P. Gibbons. "Assessing the Carbon Sequestration Potential of Managed Forests: A Case Study from Temperate Australia." Journal of Applied Ecology 43, no. 6 (2006): 1149–59. https://doi.org/10.1111/j.1365-2664.2006.01221.x.

Russell, M. B., C. W. Woodall, S. Fraver, A. W. D'Amato, G. M. Domke, and K. E. Skog. 2014. Residence Times and Decay Rates of Downed Woody Debris Biomass/Carbon in Eastern US Forests. *Ecosystems.* 17(5): 765-777., https://www.srs.fs.usda.gov/pubs/46089.

Ryan, M. G., M. E. Harmon, R. A. Birdsey, C. P. Giardina, L. S. Heath, R. A. Houghton, R. B. Jackson, D. C. McKinley, J. F. Morrison, B. C. Murray, D. E. Pataki, and K. E. Skog. 2010. A synthesis of the science on forests and carbon for U.S. Forests. *Issues In Ecology*. 13:1-16

Thom, D. and W.S. Keeton. 2019. Stand structure drives disparities in carbon storage in northern hardwood-conifer forests. Forest Ecology and Management. 442:10-20. https://www.sciencedirect.com/science/article/abs/pii/S0378112718321959

Structural complexity has a positive correlation with carbon storage in northern hardwood-conifer stands.

Woods, K. D., and C. C. Kern. 2021. Intermediate disturbances drive long-term fluctuation in old-growth forest biomass: an 84-yr temperate forest record. Ecosphere 13(1):e03871. 10.1002/ecs2.3871

Compared above-ground carbon stocks in old-growth mixed wood forest in northern MI over 84 years. "Results confirm prior suggestions of high-biomass density for old-growth temperate forests (averaging >300 Mg/ha), but, despite significant decade-scale variation, show **no overall, long-term directional change**. Study plots typically show multi-decade trends of gradually increasing biomass density, interrupted by sharp declines attributed to intermediate-severity disturbances, with recovery of pre-disturbance biomass density requiring upwards of a half-century." "While this study shows no general trend in aboveground biomass pools, it suggests that changes in disturbance regime may drive important feedbacks in biomass pool dynamics."

6. Impacts of Thinning on Growth

The following studies found that thinning from below, as expected to be widely practiced under Exemplary Forestry, either increases or does not impact the total growth of the stand (while increasing growth of crop trees).

Hoover, C. M. 2019. The carbon consequences of thinning Allegheny hardwoods: Lessons learned from a study designed to inform SILVAH development. In: Stout, Susan L., ed. SILVAH: 50 years of science-management cooperation. Proceedings of the Allegheny Society of American Foresters training session; 2017 Sept. 20-22; Clarion, PA. Gen. Tech. Rep. NRS-P-186. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 132-141. https://doi.org/10.2737/NRS-GTR-P-186-Paper12.

Hoover, C. M. and S. Stout. 2007. The Carbon Consequences of Thinning Techniques: Stand Structure Makes a Difference. *Journal of Forestry*. July/August: 266-270.

Leak, William B., and Jeffrey H. Gove. "Growth of Northern Hardwoods in New England: A 25-Year Update." *Northern Journal of Applied Forestry* 25, no. 2 (2008): 103–5. https://doi.org/10.1093/njaf/25.2.103.

Ward, Jeffrey S. 2011. Stand and individual tree growth of mature red oak after crop tree management in southern New England: 5-year results. In: Fei, Songlin; Lhotka, John M.; Stringer, Jeffrey W.; Gottschalk, Kurt W.; Miller, Gary W., eds. *Proceedings, 17th central hardwood forest conference*; 2010 April 5-7; Lexington, KY; Gen. Tech. Rep. NRS-P-78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 502-513.

Ward, J. S., and J. Wikle. 2019. Increased individual tree growth maintains stand volume growth after B-level thinning and crop-tree management in mature oak stands. *Forest Science*, 65(6), 784-795. doi:10.1093/forsci/fxz042.