MEMO

Subject: **Uncaptured Biogenic Emissions of BECCS**

From: Roel Hammerschlag

To: Sami Yassa, NRDC
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Background

Bioenergy with Carbon Capture and Storage (BECCS) promises capture of the biogenic carbon dioxide (CO_2) from biomass combustion for electric generation. From the perspective of global warming, the simple fact of capturing the biogenic CO_2 is an incomplete picture: what really matters is the net CO_2 emissions to the atmosphere due to the entire fuel supply chain. This has long been recognized in the literature, and the fossil fuel-related CO_2 (and other gases) from trucking, processing and shipping biofuel are well-documented. However, there are three prominent *biogenic* components to the net CO_2 emissions that are frequently overlooked: slash, feedstock drying and foregone sequestration.

This memo describes analysis comparing biogenic emissions (or sequestration) associated with a BECCS plant, to biogenic emissions (or sequestration) associated with a reference case absent the BECCS plant. The BECCS plant is presumed fueled by wood pellets, and presumed to operate at a constant output throughout a 40-year lifetime. For the discussion of foregone sequestration, the BECCS case is further subdivided into a clearcut case where biomass is supplied by dedicated, even-aged plantation forests and a thinning case where biomass is supplied by thinning take from an even-aged plantation forest otherwise dedicated to a non-BECCS purpose. All quantitative analysis is contained in a companion spreadsheet model.[1]

Slash

"Slash" is shorthand for harvest residues. It includes tree tops, branches, and foliage that remain on the ground after harvest. In most academic analyses of slash its quantity is estimated not by modeling or measuring the logging process, but rather by modeling the biomass in the crown of the standing tree. The crown consists of the tree top (itself defined as beginning where the stem diameter falls below a given threshold) plus all branches, and is an excellent correlate for the non-merchantable portion of the timber.[2]

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[1] Hammerschlag LLC document number NR-030(h).

[2] In this analysis we assume that the fraction of felled biomass destined for slash is equal in clearcut and thinning operations. Future work could potentially recognize a systematic difference between the two, see for example:

Though the values in Table 1 indicate that up to a quarter of aboveground biomass may remain after logging, equipment and practices exist to collect and remove large fractions thereof.[3] Logging slash has critical nutrient value for the soil,[4] so land managers will likely use their best judgment toward removing material useful for drying energy or pellet feedstock while simultaneously leaving a sufficient amount to ensure successful, future harvests.

study	species mix	slash as fraction of gross	emissions commitment *tCO_2e/t pellets*
Wade 1969	loblolly pine	11.1%	0.328
Barber & van Lear 1984	loblolly pine	25.9%	0.916
Schnepf et al 2009	mixed conifer	22.3%	0.753
Joint Research Centre 2021	European avg.	20.0%	0.657

Table 1 – Fraction of aboveground biomass left as slash after clearcut logging, and associated emissions commitments.

Since harvesters do have control over the quantity of slash remaining, and since there will be a genuine tension between utilizing slash for drying energy and leaving it on-site for soil health, I propose that the range of values shown in Table 1 are consistent with 10% to 20% of standing biomass left on-site.

Slash left on-site will decay over the next several decades; the eventual emissions associated with that decay are represented by the *emissions commitment*, the computed total, future emissions after the slash has decayed. 10% to 20% of standing biomass left onsite corresponds to an emissions commitment from **0.292 to 0.657 tCO_2e/t pellets**. Because the BECCS plant fuel demand is presumed constant each year, the quantity of slash created each year is a constant and the computed emissions commitment is as well.[5]

Though tree stumps and roots are often visually prominent in slash fields, they are rarely included in published quantifications of slash, generally due to the merchantability-focused viewpoint of the research's stakeholders, and then specifically due to the habit of estimating slash quantity from the standing tree's crown. The stumps and roots represent a substantial carbon pool and should be considered in future extensions of this work.

R.E. Benson and C.M. Johnston, *Logging Residues Under Different Stand and Harvesting Conditions, Rocky Mountains*, USDA Forest Service Research Paper INT (Intermountain Forest & Range Experiment Station, Forest Service, U.S. Department of Agriculture, 1976)

[3] Mohammad Reza Ghaffariyan, "Remaining Slash in Different Harvesting Operation Sites in Australian Plantations," 2013, 12.

[4] Mark S. Ashton and Matthew J. Kelty, *The Practice of Silviculture: Applied Forest Ecology*, 10th edition (Hoboken, NJ: Wiley, 2017), 140.

[5] Though the emissions commitment is a constant each year, the physical emissions will follow a more complex curve in early years of the BECCS plant deployment, that eventually converges to the emissions commitment value. We do not attempt to compute this curve explicitly, under the assumption the decay occurs with a time constant smaller than the climate system's sensitivity to time of emission.

Feedstock Drying

At harvest, a loblolly or slash pine bole will have a moisture content between 78% and 128%.[6,7] After harvest the boles, or hogged (chipped) biomass, can be dried to about 50% moisture content with relatively low-energy approaches that make substantial use of ambient air temperature, sunlight, or both. Feedstock for a wood pellet plant, however, must have a moisture content of 12% or less in order to manufacture finished wood pellets with a 7% moisture content.[8]

Drying to moisture contents this low requires more energy-intensive methods, and often the preferred energy source is the biomass itself. In these cases, the drying energy source is usually a mixture of bark and other low-grade feedstock; production grade feedstock; and in the case of sawmills, sawdust.

Publications agree on a heat requirement for evaporating water between 3,500 and 4,000 MJ per metric ton of water,[9,10,11] that is between 1½ and 2 times the theoretical heat of vaporization.[12] However, publications differ greatly on the gross heat energy actually required for drying, ranging from 1,400 to nearly 11,000 MJ per metric ton of pellets.[13]

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[6] Thomas L. Eberhardt, Joseph Dahlen, and Laurence Schimleck, "Species Comparison of the Physical Properties of Loblolly and Slash Pine Wood and Bark," *Canadian Journal of Forest Research* 47, no. 11 (November 2017): 1495–1505, https://doi.org/10.1139/cjfr-2017-0091.

[7] In forestry, moisture content of a sample is defined as the mass of the water in the sample, divided by the dry mass of the sample. Since most green wood can easily hold its own mass in water, this value may exceed 100% under ordinary field conditions.

[8] Augusto Uasuf, "Economic and Environmental Assessment of an International Wood Pellets Supply Chain: A Case Study of Wood Pellets Export from Northeast Argentina to Europe," 2010.

[9] Steef V. Hanssen et al., "Wood Pellets, What Else? Greenhouse Gas Parity Times of European Electricity from Wood Pellets Produced in the South-Eastern United States Using Different Softwood Feedstocks," *GCB Bioenergy* 9, no. 9 (September 2017): 1406–22, https://doi.org/10.1111/gcbb.12426.

[10] Uasuf, "Economic and Environmental Assessment of an International Wood Pellets Supply Chain: A Case Study of Wood Pellets Export from Northeast Argentina to Europe."

[11] Gerold Thek and Ingwald Obernberger, "Wood Pellet Production Costs under Austrian and in Comparison to Swedish Framework Conditions," *Biomass and Bioenergy* 27, no. 6 (December 2004): 671–93, https://doi.org/10.1016/j.biombioe.2003.07.007.

[12] 43.98 kJ/mol at 25 degrees C, see William M. Haynes and David R. Lide, eds., *CRC Handbook of Chemistry and Physics: A Ready-Reference Book of Chemical and Physical Data*, 94. ed., 2013–2014 (Boca Raton, Fla.: CRC Press, 2013).

[13] Thek and Obernberger, "Wood Pellet Production Costs under Austrian and in Comparison to Swedish Framework Conditions."

study	heat energy required for drying		harmonized	GHG emissions of heat energy		harmonized
	as published		*MJ/t pellets*	as published		*tCO_2e/t pellets*
Thek & Obernberger 2004	1021.52	kWh/t pellets	3,677	--		0.412
Bergman & Bowe 2007	5.8	GJ/m^3 lumber	10,830	398	$kgCO_2/m^3$ lumber	0.743
Uasuf 2010	0.51	t fuel/t pellets	3,947	--		0.442
Hanssen et al 2017	3.96	GJ/t H_2O	1,406	424	$kgCO_2e$/t pellets	0.424
Ray 2019	--		--	498	$kgCO_2$/Mbf lumber	0.394

Table 2 – Published values for heat energy and emissions associated with lumber and pellet feedstock drying. Where there was no published value for GHG emissions, we estimated these based on the reported heat energy and the IPCC default emission factor for wood combustion. "t" means metric ton; "GJ" means gigajoule; "Mbf" means thousand board feet.

Several sources of drying energy are described in Table 2. One source, Bergman & Bowe 2007, appears to be an outlier. Since it is a high-valued outlier removing it is a conservative choice with respect to characterizing uncaptured biogenic emissions, so we will proceed without the datapoint. This leaves us with a range of drying emissions from **0.394 to 0.442 tCO_2e/t pellets**.

Foregone Sequestration

Simplified Foregone Sequestration: Even-Aged Plantation on a Single Tract

The mass of an equal-aged forest plantation increases with a sigmoid function over time: mass accumulation is slow at first when the saplings are tiny, then it accelerates to a high rate during the plantation's middle age, and finally will slow down if left unharvested to become a mature forest. (Figure 1)

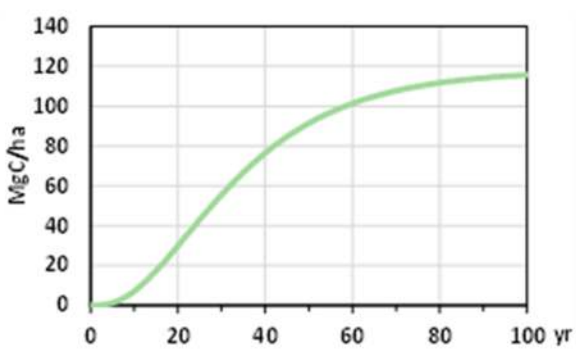

Figure 1 – Chapman-Richards growth curve for a forest exhibiting M_{max} = 118 MgC/ha; τ = 20 yr; and ɣ = 3. The growth curve shows the total carbon mass of the even-aged forest for the given number of years after planting. Do not confuse this with the rate of growth (which is the derivative of the growth curve, and has a bell shape). See Appendix A for additional discussion of the Chapman-Richards growth curve.

Figure 2 displays the same function plotted for a reference forest planted twenty-five years ago (green), and for a BECCS-case forest that is harvested and replanted at the present (blue). The mass in the replanted forest never equals what would have been achieved in the reference forest, but it eventually becomes indistinguishably close. That is why the red line depicting the difference between the two curves gets closer and closer to zero as time goes on.

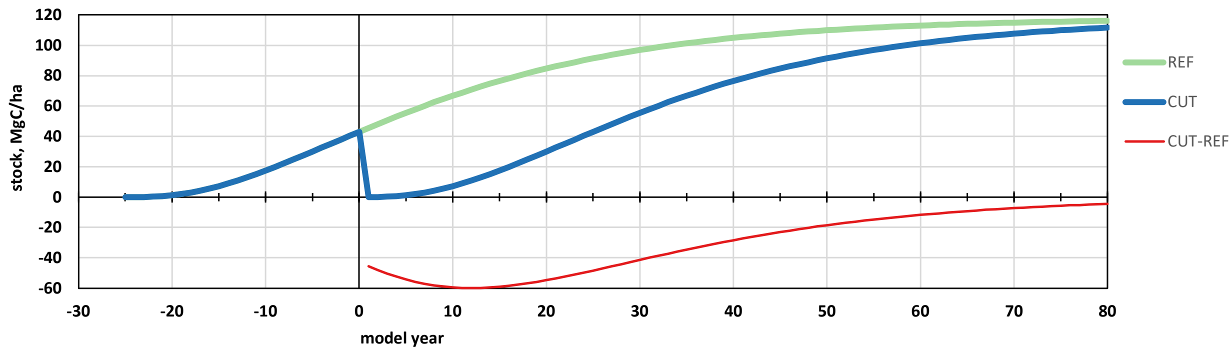

Figure 2 – The blue trace shows carbon stock in an even-aged loblolly plantation forest planted 25 years ago, followed by a clearcut harvest and re-planting on January 1 of year 1. The green trace shows how carbon stock would have evolved in the reference case, had the forest not been harvested at all. The thin red line is the difference between the two cases (blue minus green).

The BECCS case we are evaluating is defined to begin on January 1 of model year 1. Before then, the carbon lost to the atmosphere or sequestered are equal for the reference and BECCS cases. We are only interested in comparing the amount of *newly sequestered* carbon after the BECCS-related land use action occurred. This is equivalent to dropping the reference curve down so that it equals zero at year zero, which we have done in Figure 3.

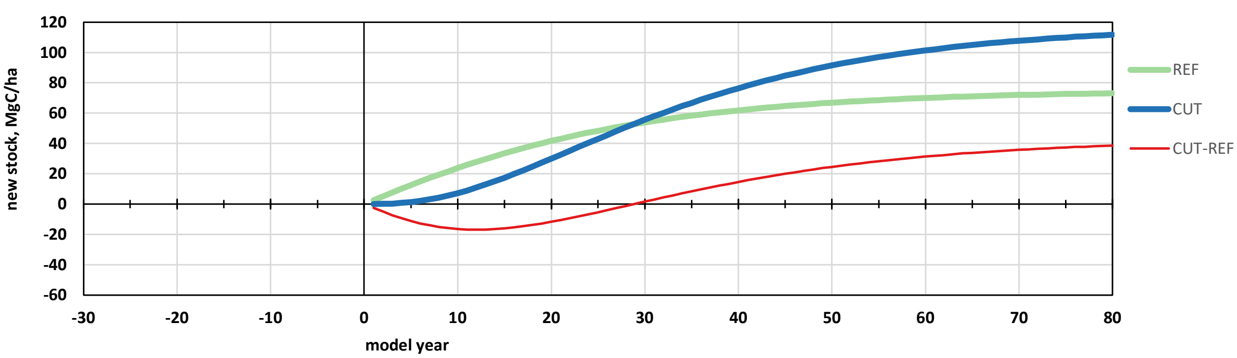

Figure 3 – *New* carbon stock gained after the harvest year.

Now things get more interesting. Left unharvested, the reference forest (green) would have been gaining mass much more quickly than the saplings starting after harvest for BECCS (blue). Eventually, though, the replanted forest reaches its highly productive middle age when the reference forest would be slowing down into maturity, and the replanted forest eventually exceeds the reference forest in *new* stock. In Figure 3, this happens at approximately year 29.

Let's zoom in to the years 1 through 40: from first harvest to the industrial planning horizon associated with the BECCS power plant (Figure 4).

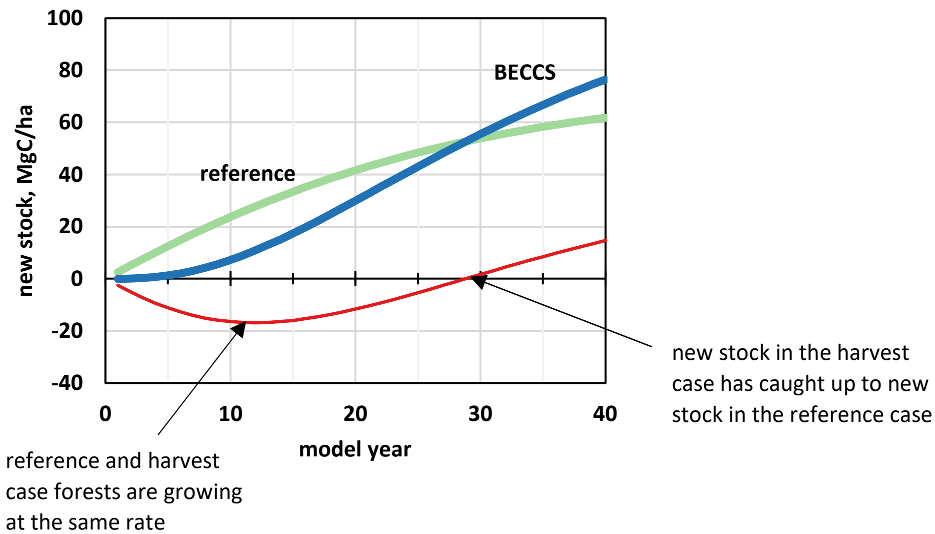

Figure 4 – Identical to Figure 3, but showing only policy-relevant years.

In the first few years after the BECC-case harvest the new saplings are still growing slowly; the reference forest would have been growing faster and a carbon debt is accrued, shown by the red line dipping below zero. At about age 12 the replanted forest passes up the reference forest in growth rate but then it still takes quite some time for the carbon debt to be repaid: only at year 29 is the replanted forest's mass finally equal to the new growth that would have happened in the reference case.

Finally, to cast the phenomenon from the point of view of the atmosphere and identify foregone sequestration, we simply flip the graph upside down and multiply by the CO_2/C mass ratio, Figure 5.

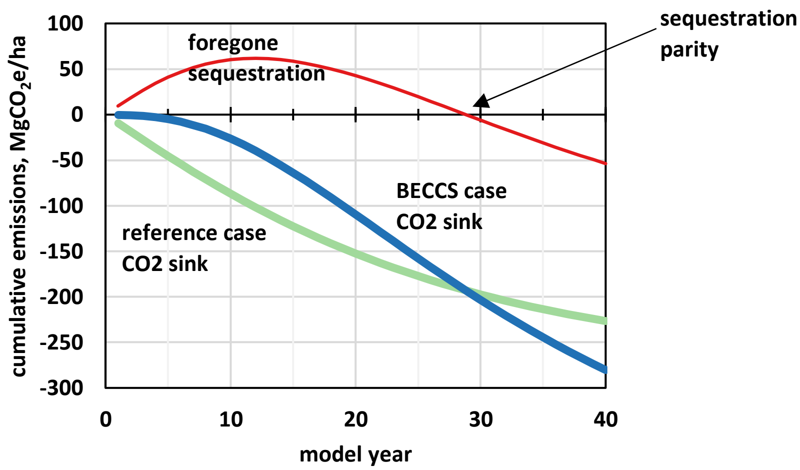

Figure 5 – CO_2 sinks and foregone sequestration.

Foregone sequestration becomes zero at year 29, the year in which the carbon debt has been repaid for this tract.

Expanding to the Entire Landscape

A utility-scale BECCS plant will draw biomass from a large number of tracts, each being harvested repeatedly according to the silvicultural rotation length. We simulated this more complex situation for a 25-year rotation, assuming that at each of the 40 years in the analysis, sufficient 25-year-old tracts exist to supply a 500 MW BECCS plant with a heat rate of 9.8 mmBtu/MWh. The result is shown in Figure 6.

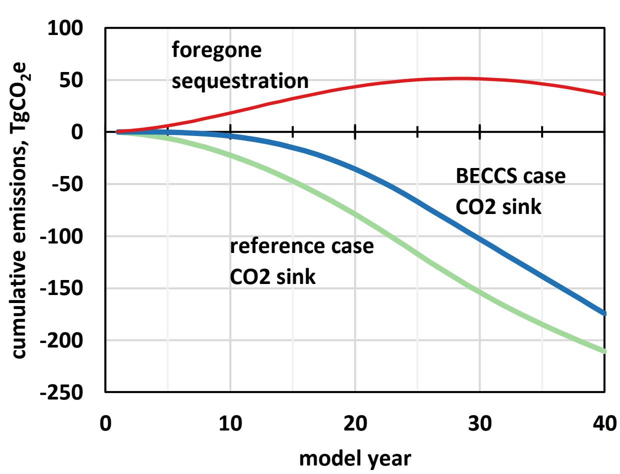

Figure 6 – CO_2 sinks and foregone sequestration in a silvicultured landscape supporting a 500 MW BECCS plant.

Applying the analysis to an entire landscape delays the achievement of sequestration parity significantly – in fact beyond our model's time horizon. During the first 25 years of the power plant's operation, more and more tracts of forest are being added to the landscape touched by the powerplant's demand, each tract experiencing its largest values of foregone sequestration in the first years after harvest. The landscape has to work (sequester) against an unrelenting tide of newly lost stock, until finally the first-harvested tracts enter their second rotation and the process can stabilize toward eventual sequestration parity.

Relating Foregone Sequestration to Energy Outputs

The quantity of foregone sequestration varies over time, in contrast to slash emissions commitment or feedstock drying each of which can be represented by a fixed, intensive value. Also unlike slash emissions commitment or feedstock drying, foregone sequestration is a cumulative value measured from the project start. In order to generate intensive values of foregone sequestration, pellet consumption must be computed on a cumulative basis as well. **Error! Reference source not found.** illustrates the computation of foregone sequestration on an intensive basis, at 10-year intervals after project initiation.

scenario parameter	units	year 10	year 20	year 30	year 40
foregone sequestration	$TgCO_2e$	18.28	43.43	51.03	36.08
cumulative plant requirements					
electricity production	TWh	43.8	87.6	131.4	175.2
heat input	EJ	0.45	0.90	1.35	1.80
pellets required	Tg	30.3	60.5	90.8	121.1
foregone sequestration	tCO_2e/t pellets	0.604	0.717	0.562	0.298

Table 3 – Translation of extensive foregone sequestration to intensive foregone sequestration. The intensive foregone sequestration (last data row of the table) is computed by dividing extensive foregone sequestration (first data row) by pellets required (fourth data row). All values are computed with the Hammerschlag LLC model developed to simulate land use impacts of a 500 MW BECCS with 35% thermal efficiency. "$TgCO_2e$" means teragrams (million metric tons) CO_2 equivalent, "TWh" means terawatt-hours (million megawatt-hours), "EJ" means exajoules.

Foregone Sequestration in Forest Thinning

Pellet feedstock can consist of commercial forestry thinnings removed mid-rotation from a plantation dedicated to conventional timber products. In this case, future carbon sequestration by the trees removed is foregone. However, the thinning induces a **release** effect, allowing remaining trees to grow at a slightly higher rate once uncrowded. The computation of foregone sequestration in the thinning case is considerably more complex than the even-aged clearcut case described above, so the methodology is elaborated in Appendix B.

Both because of the release effect, and because thinning is a less aggressive incursion into growth than clearcutting, forest thinning typically exhibits lower foregone sequestration than clearcutting. Table 4 shows our model results for thinning 15 years into the growth of a 25-year loblolly pine rotation. As with Table 3, these values represent the effect when summed across sufficient landscape to support a 500 MW BECCS plant with thinnings each year.

scenario parameter	units	year 10	year 20	year 30	year 40
foregone sequestration	$TgCO_2e$	24.04	7.16	-5.39	-32.85
cumulative plant requirements					
electricity production	TWh	43.8	87.6	131.4	175.2
heat input	EJ	0.45	0.90	1.35	1.80
pellets required	Tg	30.3	60.5	90.8	121.1
foregone sequestration	tCO_2e/t pellets	0.794	0.118	-0.059	-0.271

Table 4 – Foregone sequestration in a thinning case. Extensive values are in the first data row, and intensive (output-basis) values in the last row.

The values in Table 4 are computed under the presumption that the entire thinning take is dedicated to BECCS, while the entire clearcut harvest is dedicated to conventional (non-BECCS) forest products. We also assume that the land manager delays commercial harvest until the thinned forest is able to produce the same yield as the unthinned, 25-year rotation.

With these assumptions in place, the foregone sequestration associated with thinning is observed to accelerate quickly in the early years of plant operation, but then decrease quickly later as well. Unlike the clearcut case, thinning does achieve sequestration parity landscape-wide before the model horizon, after about 28 years (see Figure B4). Table 4 reflects this, with foregone sequestration still positive as of model year 20 but negative as of model year 30.

Variability of Foregone Sequestration

Computed foregone sequestration responds to variables from three major sources:

1. Time;
2. Forest growth characteristics; and
3. Reference and BECCS-case management regimes.

The relationship to time is treated explicitly above and in Appendix B, but our analysis is otherwise based on a single forest growth characteristic, and just two BECCS-case management regimes (one each for thinning and clearcutting). Understanding the three-dimensional field of variability in foregone sequestration requires a detailed study of its own, and is beyond the scope of the current work. We believe that the two BECCS cases assessed here are sufficient to illustrate an approximate, expected magnitude of foregone sequestration when biomass is sourced from southeastern U.S. forests.

Discussion and Recommendation

Roll-Up and Summary of Results

For ease of interpretation, we cast all GHG emission rates on an output basis as if the wood pellets were burned in an electric generation plant with 35% thermal efficiency (Table 5).

emissions source	input basis tCO_2e/t pellets	output basis tCO_2e/MWh
slash decay	0.292 – 0.657	0.202 – 0.454
feedstock drying	0.394 – 0.442	0.272 – 0.306
20-yr foregone sequestration	0.118 – 0.717	0.082 – 0.496
TOTAL uncaptured biogenic		0.556 – 1.255

Table 5 – Partial emission factors for uncaptured biogenic CO_2 streams associated with BECCS. Output-basis values assume 35% thermal efficiency of the power plant.

The Table 5 ranges for foregone sequestration reflect the thinning case at the low end and the clearcut case at the high end, and are reported as of the BECCS plant being in service for 20 years. Slash emissions commitment and feedstock drying are constant throughout the plant's lifetime and the same at year 20 as any other. All three phenomena, slash decay, feedstock drying, and foregone sequestration are of a similar order of magnitude, and sum to make a combined range (as of the plant's 20th year) of 0.56 to 1.26 tCO_2e/MWh.

Communication of results to the public or policymakers may require different presentations. One such option is provided, for convenience, in Appendix C.

System Boundary Issues

Indirect Sequestration & Emissions

Deployment of the BECCS case, though inducing new emissions from slash decay, feedstock drying, and foregone sequestration, may also induce new sequestration. In fact this is accounted for explicitly in the methodology for computing foregone sequestration of thinning in Appendix B. But are there other indirect effects we may be omitting?

Improved Land Management. If land entering the clearcut scenario was previously neglected or degraded, there will be a relative increase in sequestration due to well-managed forest growth after each BECCS harvest. Following the first few years of sapling growth, the plantation forest will likely be sequestering more quickly than the reference case. This effect is not accounted in the discussion above.

Afforestation. Our spreadsheet model draws tracts of land into account as they become available for harvest. For example, if we are modeling a clearcut scenario with a 25-year rotation, then the first year sequestration & harvest are accounted on only 1/25 of the total land that will eventually be under rotation, the second year on 2/25 of the total land, and so forth until the full rotation length (25 years) has been reached. This has little consequence if the reference land was already forested, but if it was unforested then the land owner will need to establish forest on each tract up to 25 years *before* its first harvest. The sequestration associated with initial afforestation, if it is occurring, is not modeled.

Indirect Land Use Change. Pulpwood or other medium- to low-grade timber that is favored for pellet manufacture has other uses as well. Depending on market conditions, the dedication of a given forest resource to pellet manufacture may remove it from other products' value chains and cause new land to support those other products instead. In most cases this effect will increase rather than decrease emissions induced by the biofuels policy. Research on the topic of indirect land use change is substantial but inconclusive.

Exceptions for Biogenic CO_2

At times policymakers will deem certain CO_2 emissions as inconsequential because they are biogenic. However, the atmosphere makes no distinction between CO_2 arising from one source or another – the quantity of radiative forcing is computed from the quantity of CO_2 in the atmosphere regardless of its origin. The reason that biogenic CO_2 emissions sometimes get a pass is because an *assumption* is being made that the landscape sequestration following harvest produces an equal and opposite flux. The work described in this memo is a replacement for that assumption – a quantification of both the emissions associated with harvest, and sequestration associated with regrowth. *None of the emissions described in this analysis can be granted a biogenic pass, because this analysis represents a complete accounting*.

Boundaries of Production Phases

We believe our spreadsheet model design prohibits double counting of emissions or sequestration associated with the three processes drying, slash, and foregone sequestration.

Drying Emissions. The model computes biomass demand working "backward," beginning with the heat demand of the BECCS plant, and incrementing the biomass requirement step-by-step as we work upstream in the production process. The model assigns demand for green biomass removed from the landscape, according to the heat demand of the power plant incremented by the heat demand necessary for drying at the pelletizer. If some drying occurs in the field, or in a yard at the pelletizer, the model user simulates this simply by lowering the dryer heat demand. Doing so automatically lowers the demand for green biomass removed from the forest proportionately.

Slash Decay. The user instructs the model to assume a certain fraction of any harvest is left on the ground to decay. As described above, power plant and dryer heat demand combine to specify an amount of green biomass *removed from the forest*. The model increments the demand for total biomass felled above the demand for biomass removed from the forest, according to the fraction specified by the user for decay on the ground.

Foregone Sequestration. Emissions associated with drying and slash decay are computed exclusively according to quantities of *felled* biomass. Foregone sequestration, on the other hand, is computed exclusively according to the behavior of *living* biomass. Hence, there is no potential for double-counting here either.

Implications for BECCS As a Climate Solution

For reference, the stack emissions of a combined-cycle combustion turbine plant burning natural gas at 50% thermal efficiency are 0.36 tCO_2e/MWh; and the U.S. national average grid emission rate is 0.43 tCO_2e/MWh.[14] The output-basis values in Table 5 exceed these benchmarks, which begs questions regarding the effectiveness of BECCS as a climate solution. Furthermore, demand for biomass fuel induced by BECCS has potential to create massive pressures on the landscape (see Appendix D). Policymakers should proceed slowly, and with consultation from climate and forestry scientists, before promoting BECCS at significant scales.

Respectfully submitted,

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[14] U.S. EPA, "EGRID Summary Tables 2018" (U.S. EPA, March 9, 2020), https://www.epa.gov/egrid/download-data.

Appendix A: Underlying Model of Forest Growth

The sigmoid function used in our modeling of forest growth (e.g. Figure 1, repeated here for reference) are of the Chapman-Richards type.

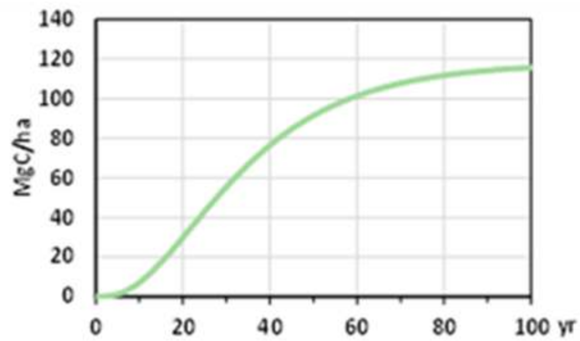

Figure 1 (duplicate) – Chapman-Richards growth curve for a forest exhibiting M_{max} = 118 MgC/ha; τ = 20 yr; and ɣ = 3. The growth curve shows the total carbon mass of the even-aged forest for the given number of years after planting. Do not confuse this with the rate of growth (which is the derivative of the growth curve, and has a bell shape).

The Chapman-Richards function follows the form:

$$M = M_{max}\left(1 - e^{-t/\tau}\right)^{\gamma}$$

where M_{max} is the maximum mass achieved by the forest, t is time in years, τ is a constant inversely related to the speed of growth also expressed in years, and γ is an empirical, unitless parameter that affects the shape of the curve. This is the function shown in Figure 1, where it is evaluated with parameters scaled to match growth of a southeastern loblolly pine forest.[15] The value of γ was held to 3.0 while the values of M_{max} and τ were fit to minimize the sum of squares between the Chapman-Richards function and the source data. $\gamma = 3$ is at the high end of values typically found in literature, but was chosen in order to suppress early growth and make the concepts related to foregone sequestration more visually apparent. Hence, the calculated, foregone sequestration derived in this analysis can be understood as a maximum.

Due to the merchantability focus of forestry literature, there has been precious little modeling or measurement of early growth. Published growth measurements and models alike were typically executed with a 5-year resolution, and beginning at year 10 or later. Early growth behavior is the critical parameter characterizing foregone sequestration, and accurate quantification thereof will not be possible until early growth is better documented. The

[15] James E. Smith et al., "Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States," General Technical Report (Forest Service, United States Department of Agriculture (USDA), 2006), 94, http://www.actrees.org/files/Research/ne_gtr343.pdf.

Chapman-Richards function was tested in this same academic environment, so its ability to accurately represent early growth is similarly unknown.

Appendix B: Foregone Sequestration of Thinning

In order to model the impact of thinning on the underlying, Chapman-Richards growth (as described in Appendix A) we apply an **index of suppression** *IS* as proposed by Hasenauer, Burkhart & Amatels[16] which they attribute to Pienaar[17] and define as

$$IS = \frac{BA_u - BA_t}{BA_u}$$

where BA_u and BA_t are the unthinned and thinned basal areas, respectively. *IS* is not a metric of flux (annual increment), but rather a time-dependent metric of stock. It is the fraction, at some point in time at or after thinning, of baseline basal area that is lost due to the thin. Pienaar postulated that *IS* evolves over time according to the form

$$IS_{t2} = {IS_{t1}}^{\beta_1} e^{-\beta_2 (t_2 - t_1)}$$

and fit field data to determine $\beta_1 = 0.77$ and $\beta_2 = 0.103\ yr^{-1}$ for their published, experimental case of slash pine.[18] IS_{t1} is simply the fraction of basal area initially removed.

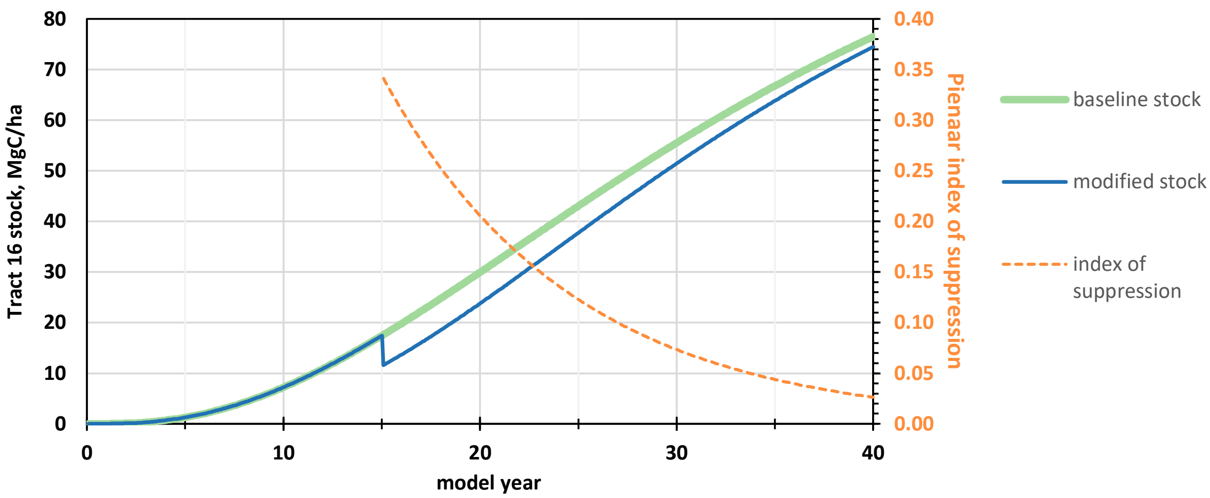

Figure B1 – Behavior of modeled, loblolly pine stock with and without thinning after 15 years of growth.

[16] H Hasenauer, H E Burkhart, and R L Amateis, "Basal Area Development in Thinned and Unthinned Loblolly Pine Plantations" 27 (1997): 7.

[17] L V Pienaar, "An Approximation of Basal Area Growth after Thinning Based on Growth in Unthinned Plantations," *Forest Science* 25, no. 2 (1979): 223–32.

[18] *IS* per Pienaar is based on basal area, whereas the BECCS simulator estimates forest mass, which is proportional to volume rather than area. This has no impact on Pienaar's equation when all trees in the thinned forest are identical. This is a reasonable, simplifying assumption for even-aged plantation forests, but future refinement of this methodology may account for different responses on a volume vs. basal area basis when thinning is from below.

Figure B1 shows modeled, loblolly pine stock from initial planting up to the 40-year time horizon associated with the BECCS model. The green trace is the same stock curve shown in Figure 1. The blue trace shows stock response to a thinning operation that removes 25% of aboveground stock volume (mass) after 15 years of growth. The orange, dashed line is the Pienaar index of suppression, with values shown on the right edge of the chart.

Thinned forest initially loses even more than the 25% of aboveground stock felled, due to natural mortality in response to the shock of thinning – this is the effect observed by Pienaar and driving the value of parameter $\beta_1 = 0.77$. Thereafter, the forest grows more quickly than it would have without thinning, as apparent from the modified stock curve (blue) gradually approaching the reference stock.

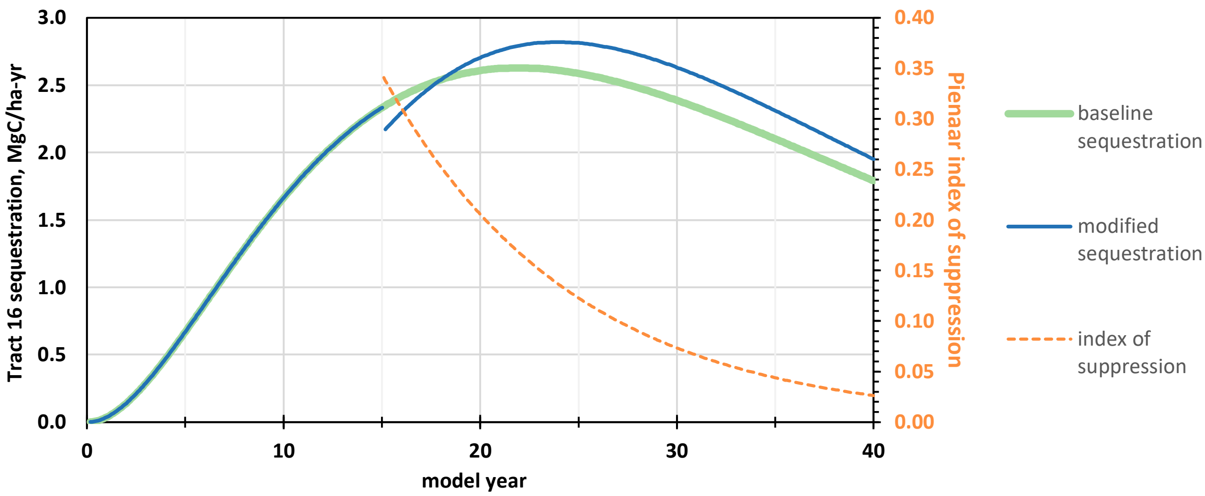

Figure B2 – Sequestration response of loblolly pine to thinning after 15 years of growth.

This release effect is manifestly visible if we plot annual increment (sequestration) rather than gross stock (Figure B2). Only a few years after thinning, the annual increment of the thinned forest exceeds that of the reference case and remains that way indefinitely. However, in a practical application the land manager will eventually harvest the thinned stand, so that the stock curve of Figure B1 will actually follow the trajectory shown in Figure B3.

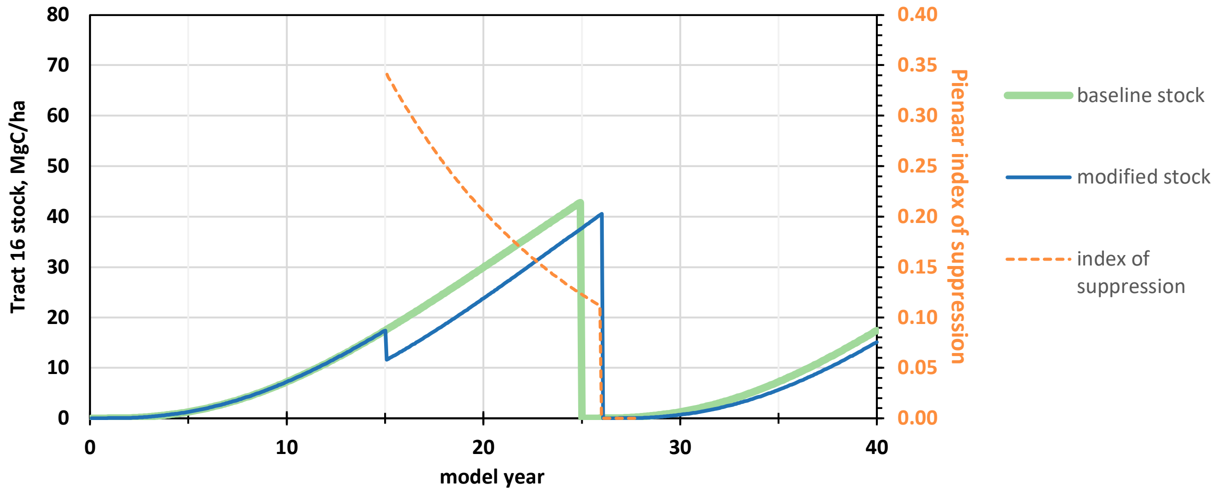

Figure B3 – Land manager's response to thinning.

The land manager does delay harvesting somewhat, in order to retrieve the same quantity of board feet per hectare as they are accustomed to (as would be provided by the reference case). The BECCS model accounts for this, and as shown in Figure B3 with the model parameters set as described in this memo, the land manager needs to delay only one year to achieve sufficient harvest.

A utility-scale BECCS plant will draw biomass from a large number of tracts, each being harvested repeatedly according to the silvicultural rotation length. We simulated this more complex situation for a 25-year reference rotation length, assuming that at each of the 40 years in the analysis, sufficient 25-year-old tracts exist to supply a 500 MW BECCS plant with a heat rate of 9.8 mmBtu/MWh. The computed foregone sequestration in this case is as shown in Figure B4.

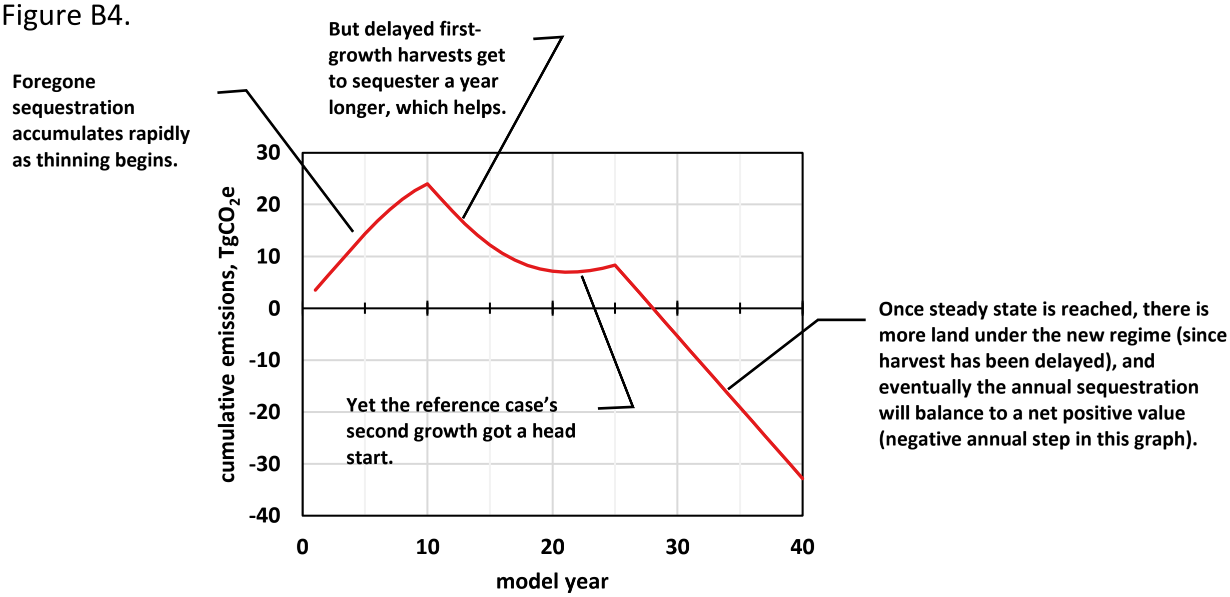

Figure B4 – Foregone sequestration in the thinning case.

The behavior of foregone sequestration in the thinning case is more complex than in the clearcut case. At first, there is a strong increase in foregone sequestration as forest mass (and hence ability to sequester) is lost. But because the land manager is delaying harvests in response, each tract gets a chance to sequester a bit longer before getting clearcut, an effect which starts showing up in Figure B4 at year 11, the number of years after thinning (at age 15) that the forest is harvested (at age 26 – would have been 25 without thinning). Yet, the reference forest did have a head start on second growth and these two forces oppose each other to produce the bowl-like shape in years 11 through 25.

Finally, steady state is reached at model year 26. Due to the delayed harvest, a slightly larger gross landscape is required to support the new forestry regime, inducing more capacity for sequestration. At this point the annual increment to foregone sequestration becomes negative, and the curve heads linearly downward indefinitely.

Appendix C: Alternative Presentation of Results

Communication of uncaptured biogenic emissions to the public or the policymaking community may require a conceptually simplified approach. This applies especially to the case of foregone sequestration. To provide NRDC with tools for doing so, we offer Tables C1 and C2 below. Relative to Table 5 these offer the following tools for effective communication of results:

- Each parameter includes a nominal ("average") value in addition to maximum and minimum;
- The clearcut and thinning cases are presented separately, rather than intermingled;
- Duration-dependent foregone sequestration is replaced by the concept of foregone sequestration *risk*, a maximum or average value that can be encountered throughout the plant's lifetime.

	emissions, $kgCO_2e/MWh$		
emissions source	minimum	nominal	maximum
slash decay	202	328	454
feedstock drying	272	289	306
foregone sequestration risk	97	374	499
TOTAL uncaptured biogenic	**571**	**990**	**1,259**

Table C1 – Uncaptured biogenic emissions associated with the *Clearcut* BECCS case.

	emissions, $kgCO_2e/MWh$		
emissions source	minimum	nominal	maximum
slash decay	202	328	454
feedstock drying	272	289	306
foregone sequestration risk	0	309	794
TOTAL uncaptured biogenic	**474**	**926**	**1,554**

Table C2 – Uncaptured biogenic emissions associated with the *Thinning* BECCS case.

In each of the two cases, the maximum foregone sequestration risk is the highest output-basis foregone sequestration encountered prior to the 40-year model horizon. It represents the strongest contribution to climate forcing that will occur during the plant's lifetime. The nominal foregone sequestration risk is computed as the average value of foregone sequestration between start of operation and reaching sequestration parity. The minimum foregone sequestration risk is the greater of zero, or foregone sequestration at the model horizon. Minimum sequestration risk is nonzero only if sequestration parity would be reached after the model horizon.

In terms of policy goals, attention to the maximum foregone sequestration risk would be consistent with concern for near-term tipping points in the climate system, while attention to the minimum foregone sequestration risk would be consistent with confidence in a climate system that is stable (linearly behaved) through the model's time horizon.

Appendix D: Issues of Landscape Scale

The Hammerschlag LLC BECCS model computes, as an incidental output, the total quantity of landscape required to support the modeled BECCS plant, depending on which harvest types are being modeled. The values of these outputs are rather stunning in their size and should generate concern, irrespective of the emissions balance. Extreme demands on land use can have negative environmental and economic repercussions, and can even turn the computed emissions balance upside down through indirect land use change.

Electric generating plants benefit from an efficiency of scale and are generally built as large as practically possible. As a rule of thumb, fossil-fueled power plants are in the neighborhood of 1 MW in size – that is, they generate 1 MW of electricity when running at 100% capacity. Yet it is possible to construct plants much smaller or much larger. The Drax Power Station in North Yorkshire, England has a capacity of approximately 3.9 MW, of which 2.6 MW is fueled by biomass as of 2021. Drax is by far the largest biomass-fired electric generator in the world, and draws the majority of its fuel from outside of England. Yet, 2.6 MW is an ordinary size for a central electric generating plant, so a substantial deployment of BECCS throughout the world could create many more plants with similar biomass demand.

As an exercise, we computed the quantity of land required to support a 1 MW biomass plant operating at a real-world 85% capacity factor:

harvest type	ha required
herbaceous crop	0.5 million
short rotation woody crop	1.0 million
clearcut	1.9 million
forest thinning	16.9 million
forestry waste	*tbd*
agricultural waste	*tbd*
industrial waste	*tbd*
comparators	**ha**
entire size of England	13.3 million
all woodland in England	1.3 million

We have not yet gathered sufficient data to estimate the landscape requirements of biofuel scavenged for forestry, agricultural or industrial waste, but as an order of magnitude one could rely on the completed computation for forest thinning since this is also a scavenged approach. Common sense implies that there is far from enough spare land available to support more than a small fraction of the world's electrcity demand with biomass.