Supplementary 4 – AD Pathway

The avoided deforestation pathway estimates the carbon implications of avoided forest conversion in New England states. For each state, we multiply the 30-year business-as-usual acres of forest loss by our estimate of carbon and sequestration loss per acre for each of these conversion categories. We estimate three tiers of potential avoided deforestation: 100%, 75%, and 50%.

Forest Conversion

For the BAU forest loss estimate, the study uses forest loss data by state in New England from Grant Domke and his team at the USFS (Walters et al 2021); these data underlie estimates summarized in Domke et al 2021 and provide acres of forest lost to three land categories over the period 1990-2019 (Table 1): settlements, cropland, wetland, and "other land".

Other land is defined here following IPCC 2006 as a category that "…includes bare soil, rock, ice, and all land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available." (IPCC 2006) Conversations with USFS have indicated that this category may include some areas of bare soil, rock and ice but also include errors in the data where a land-use category was not included and may reflect conversion to settlements as most forestland conversion in New England is to settlements: roughly 50% of forestland lost in New England is to settlements (Table 1).

Forest land in New England is also being lost to solar development, though consultation with USFS staff on the FIA dataset has shown that there is not a robust way to isolate forest loss to solar development in FIA data yet.

Table 1: Forest Loss Estimates (acres)

Forest Converted to Non-forest Land Use Types (annual average acres, 1990-2019)							
State	**CT**	**ME**	**MA**	**NH**	**RI**	**VT**	**New England Total**
Wetland [1]	1,701	4,820	721	3,352	-	1,212	11,807
Cropland	-	2,371	2,119	2,765	630	6,474	14,358
Other Land	44	1,867	443	132	-	229	2,716
Settlements	1,652	12,392	2,874	4,585	926	5,761	28,191
Total average annual acres of forest loss (1990-2019)	**3,398**	**21,450**	**6,156**	**10,835**	**1,556**	**13,676**	**57,071**
% of conversion to settlements (excluding water)	**49%**	**62%**	**51%**	**50%**	**40%**	**41%**	**52%**
Forest Converted to Non-forest Land Use Types (total acres, 1990-2019)							
State	**CT**	**ME**	**MA**	**NH**	**RI**	**VT**	**New England Total**

Wetland [1]	51,027	144,606	21,622	100,572	-	36,374	354,200
Cropland	-	71,117	63,555	82,953	18,904	194,225	430,753
Other Land	1,334	56,019	13,294	3,954	-	6,870	81,471
Settlements	49,569	371,769	86,215	137,563	27,775	172,825	845,717
Source: Walters et al 2021							
Notes: [1] We do not include loss to wetland in our analysis. [2] Other land is defined here following IPCC 2006 as a category that "…includes bare soil, rock, ice, and all land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available." (IPCC 2006)							

Discussion of Other Forest Loss Estimates

Forest loss is an area of focused and active research using remote sensing methodologies; a large literature base exists on improving remote sensing methods; and there are some well-known results with attribution to various drivers (e.g. Hansen et al 2010; Curtis et al 2018; Harris et al 2017). Efforts to identify forest loss and attribute loss to various natural and anthropogenic drivers (urbanization, agriculture, forestry) are also occurring at the U.S. national scale and within New England. Table 2 summarizes forest loss estimates in the literature that were provided by state using a consistent methodology.

Table 2: New England-wide forest loss estimates in the literature

Source	Forest loss estimates
Jeon et al 2014 (also with Olofsson)	Remote sensing-based analysis of land use change, not including areas of forest harvest, mapped across New England (Maine excluded) between 1990 and 2005. A total of 133,000 ha were deforested for use as residential or commercial development. The net forest loss was 129,000 ha (2.8% of the forest present in 1990).
Olofsson et al 2016	Remote sensing-based assessment; source of the estimates of forest loss used in W&W 2017 report. Concluded that 387,000 ha of forest had been converted to other land uses since 1985, primarily from low density residential development. Forest expansion to non-forest areas was found to be statistically insignificant.
Ducey et al 2016	Forest loss numbers by state are cited from W&W; also use NLCD land cover data from 2001, 2006 and 2011. "Forest cover change is strongly linked to demographic variables throughout this region. Forest cover loss is most pronounced along the urban fringe, where population growth is greatest."
Thorn et al 2016	Used geographic predictors (elevation, slope, distance to roads, distance to cities, population density, etc…) of forest loss to development between 2001 and 2011. NLCD data for 2001, 2006 and 2011. The two most important variables in the BRT were "population density" and "distance to road", which together made up 55.5% of the variation for 2001–2011, 49.4% for 2001–2006 and 42.9% for 2006–2011.
Thompson et al 2017	Projects forest cover change using recent trends from 1990-2010. Reclassified land cover maps from 1990, 2000 and 2020 into (1) a single forest class; (2) high density development; (3) low density development; and (4) an "all other" class. Over the full reference period, 20,265 acres/year and 1,156 acres/year of forest were lost to low- and high-density development, respectively. Forest loss was concentrated in suburban areas, particularly around Boston. Distance to developed land was the strongest predictor of forest loss. The 43,243 square mile study area used in the study included all of Massachusetts and New Hampshire, 93% of Vermont, 99% of Connecticut, and approximately 33% of Maine. During the 50-year simulations conducted, 1,071,202 ha of

	forests were converted to developed uses throughout the study area, resulting in a decline in forest cover from 75.2% in 2010 to 71.2% in 2060. The study also notes that forest loss rates vary by reference period.
[Duveneck and Thompson 2019](#)	Looked at drivers of change to the Recent Trends projections in forest loss, harvest and growth for New England using loss estimates developed in Olofsson et al 2016 and Thompson et al 2017. Looked at the projections in light of drivers of change to gauge their relative importance both in the aggregate and individually. Concluded that without future land use or climate change (control scenario), aboveground carbon on the New England landscape would increase by 53% from 2010 to 2060. Climate change further increased aboveground carbon by 8% compared to the control while land use reduced aboveground carbon by 16%. Harvest had a greater impact on aboveground carbon in 2060 than did forest conversion.

Finally, to emphasize the range of estimates available for forest loss, we show a comparison of 22 different published estimates of forest cover or tree cover in New England (Figure 1). These estimates indicate wide variability of forest loss estimates across datasets.

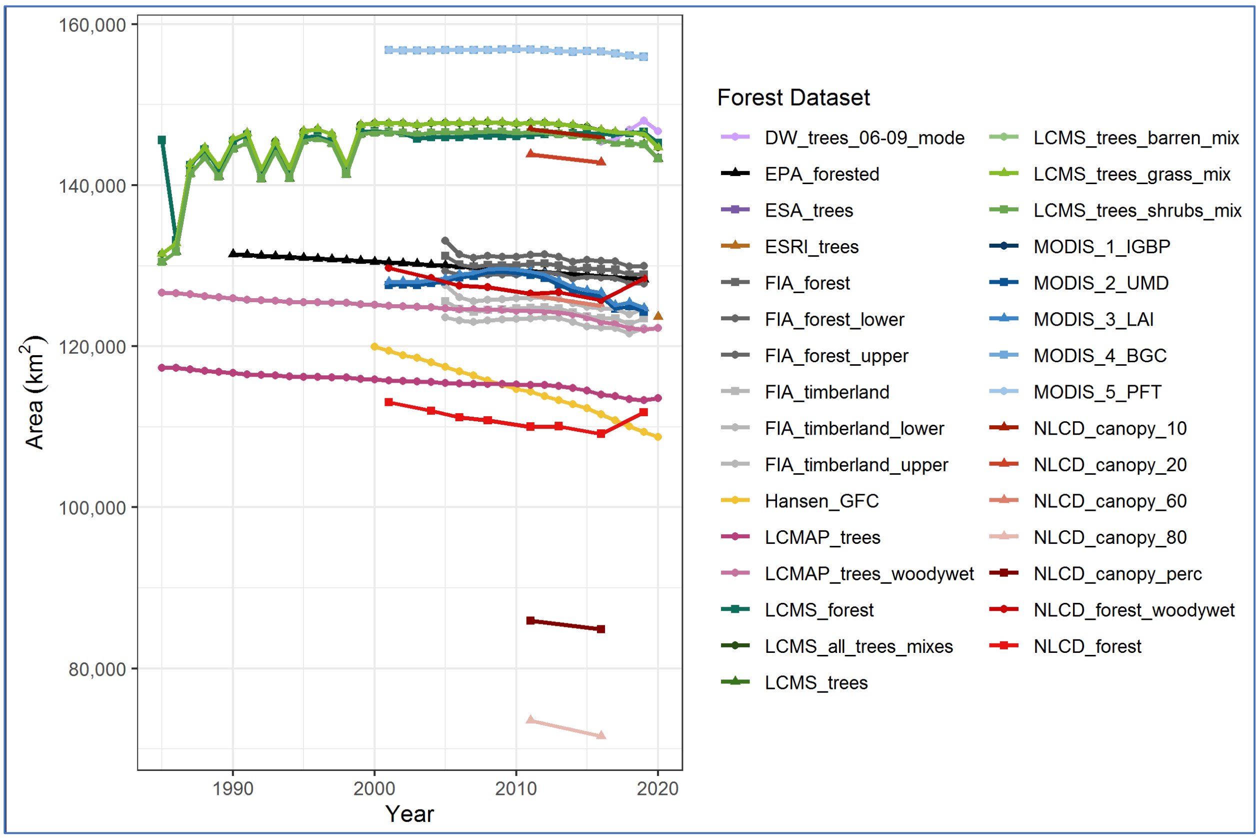

Figure 1: Tree and Forest Area Estimates in New England

Source: Pasquarella et al 2022

Table 3 summarizes the state-level forest loss estimates available from the literature and used in the study as the low, medium, and high forest loss estimates. Study estimates for the combined pathways reflect the medium forest loss scenario. The tier selection (100%, 75%, and 50%) is applied to the forest loss estimate, effectively reducing the quantity of forestland acres assumed to be retained (avoided deforestation) on the landscape and thereby the carbon losses associated with forest loss.

Table 3: State-level forest loss estimates in New England

State	**Forest Loss to Development (acres/year, 1990-2010) LOW ESTIMATE**	**Forest Loss to Settlements (acres/year, 1990-2019) MEDIUM ESTIMATE**	**Forest Loss to Settlements, Cropland, and Other Land (acres/year, 1990-2019) HIGH ESTIMATE**
Source	LCMAP [1]	Walters/FIA 2021	Walters/FIA 2021
Connecticut	1,414	1,652	5,180
Maine	3,246	12,392	18,100
Massachusetts	3,202	2,874	10,621
New Hampshire	2,222	4,585	10,901
Rhode Island	359	926	1,041
Vermont	633	5,761	12,329
New England Total	**11,076**	**28,191**	**58,172**
Notes: [1] LCMAP forest cover loss reflects total net tree cover loss to development, cropland, barren, and wetland only.			

Forest Gain in Domke, Walters/FIA Data

Walters et al 2021 also provide forest gain estimates, reflecting acres for which FIA data show a conversion of water, cropland, other land, and settlements to forestland. This section describes these data, and the researchers' reasons for not including the potential carbon-related impacts of forest gain that could be derived from the data.

As FIA is a forest use-based system, forest gain acres will reflect, for example, acres of abandoned cropland because in New England abandoned land will naturally revert to forest. As such, these acres classified as gained do not likely represent mature forest or intentional reforestation efforts, as the reforestation opportunity in New England is not as great as in other areas of the country. A forest cover-based approach, such as the remote sensing methodologies described above, would not count these acres as forestland because vegetation would not be present in sufficient quantity to appear via remotely sensed imagery. This difference necessarily results in different forest loss estimates across methodologies. Due to forest gain acres present in the FIA data, Walters et al 2021 show a net forest change in New England that is smaller when forest gain estimates are added to the forest loss estimates: these data show a net forest loss to settlements of 10,877 acres/year across all New England states as shown in Table 4.

Table 4: Forest gain estimates (acres)

Non-Forest Converted to Forest (annual average acres, 1990-2019)							
State	**CT**	**ME**	**MA**	**NH**	**RI**	**VT**	**New England Total**
From Water	2,190	1,050	0	0	0	305	3,545
From Cropland	582	1,053	474	2,039	125	1,148	5,421
From Other Land	338	2,039	74	72	633	47	3,203
From Settlements	3,710	7,178	2,492	2,430	264	1,240	17,314
Total	**6,820**	**11,321**	**3,040**	**4,541**	**1,022**	**2,740**	**29,484**
Non-Forest Converted to Forest (total acres, 1990-2019)							
State	**CT**	**ME**	**MA**	**NH**	**RI**	**VT**	**New England Total**
From Water	65,705	31,506	0	0	0	9,143	106,354
From Cropland	10,131	31,580	14,209	61,183	3,756	34,446	155,305
From Other Land	10,131	61,183	2,224	2,150	19,002	1,408	96,099
From Settlements	111,296	215,352	74,774	72,896	7,907	37,189	519,415
Total	**197,264**	**339,621**	**91,206**	**136,229**	**30,666**	**82,187**	**877,173**
Net Forest Change (average annual acres, 1990-2019)							
State	**CT**	**ME**	**MA**	**NH**	**RI**	**VT**	**New England Total**
Water	489	-3,770	-721	-3,352	0	-908	-8,262
Cropland	582	-1,318	-1,645	-726	-505	-5,326	-8,937
Other Land	293	172	-369	-60	633	-182	488
Settlements	2,058	-5,214	-381	-2,156	-662	-4,521	-10,877
Total Net Change	**3,422**	**-10,130**	**-3,116**	**-6,294**	**-534**	**-10,937**	**-27,588**
Source: Walters et al 2021							

Another example of the impact of forest gain estimates on total net change is detailed in Butler et al 2015 where the USFS estimates (using FIA data) that between the 2007 and 2012 inventories, the Southern New England states of CT, MA, and RI lost a total of 99,000 acres of forest land, with 58% of the loss attributed to commercial and residential development (Figure 2). Over this time, the USFS notes that the forest in the Southern New England states of CT, MA and RI gained 175,000 acres and concludes there was no significant net change in forest land acres (Butler et al 2015), so the forested areas remained forest. Gains in forest were primarily attributed to developed acres reverting to forest (64%).

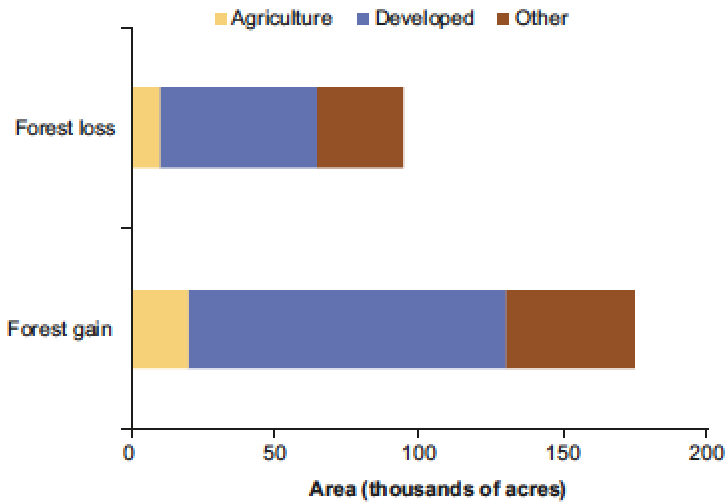

Figure 2: Area of forest gain and loss by land use between 2007 and 2012, Southern New England.

Source: [Butler et al 2015]

While FIA data suggest that forestland loss estimates are lower than other estimates in New England states, particularly in Southern New England, the current study does not use forest gain data from FIA or include the carbon implications of forest gain in the final pathway estimates. The reasons for doing so are multiple. First, the accuracy of forest gain estimates is questionable when considering information contained in Olofsson 2016. Olofsson 2016 presents charts as shown in Figure 3 that highlight differences between remotely sensed estimates and FIA data. While direct comparison is not appropriate given the different methodologies and definitions of forest being used across these studies – FIA is forest use and Olofsson 2016 is forest cover – the deep decreases and increases evident in the FIA data are notable, particularly for CT, where net forest change differs the most from alternate estimates (as shown in Table 4, CT shows a net forest *gain* of ~3,422 acres). There are also a relatively small number of FIA forested plots in CT (306 plots) and other Southern New England states (e.g., Rhode Island has 130 plots) relative to the Northern New England states (e.g., New Hampshire has 1,015 plots; Maine has 3,144 plots).

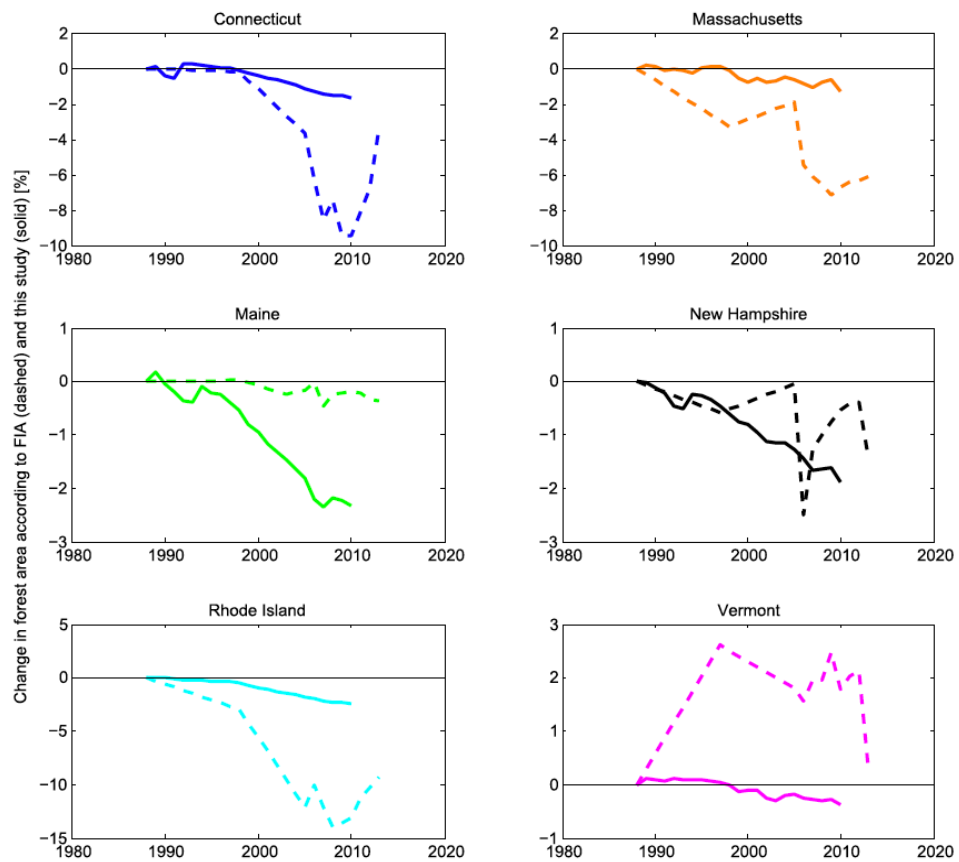

Figure 5. Forest loss as percentages of the forest area in 1986 based on FIA data (dashed) and the results of this study (solid).

Figure 3: Forest loss as percentages of the forest area in 1986 based on FIA data (dashed) and the results of this study (solid).
Source: Olofsson et al 2016

In addition to potential inconsistencies in the data suggested by the Olofsson 2016 charts above, the carbon implication of forest "gain" acres in the FIA data is difficult to assess: not all acres will stay abandoned/revert to forest, and for those that do, mature forest is unlikely to be present in the 30-year time period of analysis. In many cases, the forest "gain" acres may represent the *potential* for mature forest on any given acre, but there is not a reasonable way to determine accurately the number of acres that would result in mature forest. For this reason, forest gain and loss figures are different from a carbon implication perspective. When an acre of forest is lost to development or cropland, the current study assesses the average carbon loss per acre of forestland implicitly counting that acre as relatively mature forestland. The forest gain acres, on the other hand, may be seedlings in year 1 of the analysis and will sequester carbon but will not be equivalent to losing mature acres of forestland. Therefore, forest carbon storage and sequestration may decline even as forest acres are gained according to the forest use methodology employed by FIA if mature forest is lost but gain some percentage of early successional forest over 30-years. These unknowns and nuances led the researchers to omit the carbon implications of potential forest gain from the current study.

Carbon Implications of Forest Conversion

The conversion of forestland to other land uses such as settlements and cropland has an impact on both the stocks and sequestration potential of the converted acres of forest. The impact of avoided conversion is an area of current research to address the limited evidence on which forest land is being converted, to what uses, and what the carbon implications of the conversions are in New England. Considering limited data, the current study uses average carbon densities per acre calculated for the baseline and applies IPCC and other assumptions, including from studies specific to New England, to estimate the carbon implications of forest loss to different land use categories. The study follows international GHG inventory reporting guidelines (IPCC 2006) that recommend capturing the impact on carbon stocks and flows by estimating the difference between the quantity of carbon on a converted land area before and after the conversion. It is important to note that because losses are calculated based on average carbon density per acre of forestland, forestland losses are assumed to occur from fairly mature forest. To the extent that forestland loss is not mature forest but less carbon dense forested areas where trees are younger, these estimates may overestimate aboveground carbon loss.

Conversion to settlements

According to IPCC guidelines, settlements experience rapid loss of carbon in the year of conversion, followed by gradual increases in carbon pools. (IPCC 2006) Domke et al assume a 100% loss in biomass upon forest conversion to settlements. The current study takes a different approach based on a New England-specific factor: forestland converted to settlements is assumed to lose 70% of the aboveground carbon stock but to retain 30% on the developed acres as street and yard trees (Raciti et al 2012). This proportion is applied to average annual carbon sequestration as well. Soil carbon impacts are not included and would be impacted by conversion to settlements; the estimates are therefore likely an underestimate of carbon loss resulting from conversion to settlement.

Conversion to cropland

The study uses IPCC guidelines for the conversion of forestland to cropland. Under this methodology, all aboveground biomass is removed upon conversion of forestland to cropland with one year of growth from cropland added back in. IPCC estimates that the carbon stock in cropland after one year of growth is 0.91 metric tons of carbon per acre (IPCC 2006). This estimate for the loss of forestland to cropland in New England states is used and is applied to average annual carbon sequestration as well, i.e., one year of sequestration is added back in.

Conversion to other land

Based on consultation with USFS staff, we understand that losses represented in the "other land" category may in many cases reflect data gaps where the specific loss category was not indicated in the FIA data. However, these are losses from forested areas where they convert to the other land category as defined as "bare soil, rock, ice, and all land areas that do not fall into any of the other five categories" (IPCC 2006). Because conversion to settlements is the most frequent conversion type in the New England region, conversion to other land is assumed to reflect conversion to settlements and the loss to settlements carbon ratio of 70% lost/30% retained on the converted acres is applied. This proportion is applied to average annual carbon sequestration as well.

Following this methodology for forest conversion, Table 5 shows the average per acre carbon stock and sequestration loss used for forest conversion in each of the New England states. These stock and sequestration losses are considered gains when forest loss is avoided; the estimates are applied to the avoided forest loss acres under the tier selected to arrive at the total carbon benefit (carbon stock and sequestration) of avoided deforestation.

Table 5: Estimated carbon stock and sequestration losses from forestland conversion

State	CT	ME	MA	NH	RI	VT
Carbon Stock Losses (tons/acre forestland)						
C stock loss from conversion to cropland	50.56	32.05	49.67	43.02	46.89	46.02
C stock loss from conversion to other land	36.51	23.40	35.88	31.17	33.91	33.29
C stock loss from conversion to settlements	36.51	23.40	35.88	31.17	33.91	33.29
Carbon Sequestration Losses (tons/acre forestland)						
C seq loss from conversion to cropland	0.48	0.14	0.39	0.27	0.31	0.33
C seq loss from conversion to other land	0.34	0.10	0.28	0.19	0.22	0.23
C seq loss from conversion to settlements	0.34	0.10	0.28	0.19	0.22	0.23

Note: Data are based on the most recent year from Walters et al 2021 (2019/2020).
Source: Authors' calculations based on Walters et al 2021; FIA Evalidator data; IPCC 2006; Raciti et al 2012.