

Older eastern white pine trees and stands sequester carbon for many decades and maximize cumulative carbon

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1

2 Abstract

3 Pre-settlement New England was heavily forested, with some trees exceeding 2 m in diameter. New
4 England's forests have regrown since farm abandonment and represent what is arguably the most
5 successful regional reforestation on record; the region has recently been identified as part of the
6 "Global Safety Net." Remnants and groves of primary "old-growth" forest demonstrate that native tree
7 species can live for hundreds of years and continue to add to the biomass and structural and ecological
8 complexity of forests. Forests are an essential natural climate solution for accumulating and storing
9 atmospheric CO₂, and some studies emphasize young, fast-growing trees and forests whereas others
10 highlight high carbon storage and accumulation rates in old trees and intact forests. To address this
11 question directly within New England we leveraged long-term, accurate field measurements along with
12 volume modeling of individual trees and intact stands of eastern white pines (*Pinus strobus*) and
13 compared our results to models developed by the U.S. Forest Service. Our major findings complement,
14 extend, and clarify previous findings and are three-fold: 1) intact eastern white pine forests continue to
15 sequester carbon and store high cumulative carbon above ground; 2) large trees dominate above-
16 ground carbon storage and can sequester significant amounts of carbon for hundreds of years; 3)
17 productive pine stands can continue to sequester high amounts of carbon for well over 150 years.
18 Because the next decades are critical in addressing the climate crisis, and the vast majority of New
19 England forests are less than 100 years old, and can at least double their cumulative carbon, a major
20 implication of this work is that maintaining and accumulating maximal carbon in existing forests –
21 proforestation - is a powerful near-term regional climate solution. Furthermore, old and old-growth
22 forests are rare, complex and highly dynamic and biodiverse, and dedication of some forests to
23 proforestation will also protect natural selection, ecosystem integrity and full native biodiversity long-
24 term. In sum, strategic policies that grow and protect existing forests in New England will optimize a
25 proven, low cost, natural climate solution for meeting climate and biodiversity goals now and in the
26 critical coming decades.

27

28 **Keywords:** carbon accumulation, proforestation, chronosequence, tree volume measurements, old-
29 growth forest, ecological integrity, ecological resilience

30

31 **Running title:** Carbon in eastern white pines and stands

32

33 **Introduction**

34 A global priority for the climate has long been reducing ongoing emissions of heat-trapping
35 greenhouse gases (GHGs) produced by burning carbon-based fuels. While essential, less attention has
36 been given to the importance of simultaneously increasing carbon dioxide (CO₂) removal (CDR) by
37 natural systems. Clearing forests, draining and developing wetlands, and degrading soils account for
38 one-third of all the CO₂ added to the atmosphere by humans since the beginning of the industrial
39 revolution. Together these ongoing actions continue to add approximately 1.5 PgC/year (1 Pg is 10¹⁵
40 grams or 1 billion metric tonnes). Burning wood and plant-derived liquid fuels adds even more CO₂,
41 and current forest management practices keep forests relatively young and limit their potential to
42 accumulate carbon above and below ground and keep it out of the atmosphere. Two recent
43 Intergovernmental Panel on Climate Change (IPCC) reports outlined the urgent and unprecedented
44 imperative to halt CO₂ emissions and remove additional CO₂ from the atmosphere (IPCC, 2018, 2019).
45 These reports, including the recent 1.5°C IPCC special report, identify forests as playing a major role.
46 However, for CDR they focus primarily on afforestation (planting new forests) and reforestation
47 (regrowing forests) and do not take into account the climate mitigation and adaptation benefits of
48 growing existing natural forests termed “proforestation” (Moomaw et al., 2019; Cook-Patton et al.,
49 2020).

50 Even achieving the goal of “zero net carbon” to limit global average temperatures to 1.5°C will still
51 increase temperatures above the current rise of 1.1°C. This will result in additional disruption of the
52 climate system and additional adverse consequences presently experienced; impacts are
53 interconnected. To avoid ever-more serious consequences of a changed climate, the goal must be to
54 become net carbon *negative* as soon as possible. Using the strategies of natural reforestation and
55 particularly proforestation are among the most effective and least costly means for reducing the
56 atmospheric stock of carbon as will be illustrated by the findings reported in this paper. The power of
57 natural solutions – particularly growth and regeneration of natural forests – varies regionally, and has
58 recently been identified as being even more robust than previously considered (Cook-Patton et al.,
59 2020).

60 A second and perhaps even more urgent priority is the strong protection of intact biodiverse natural
61 systems as outlined in the Global Assessment Report on Biodiversity and Ecosystem Services
62 (Intergovernmental Science-Policy on Biodiversity and Ecosystem Services, 2019). This joint
63 climate/biodiversity priority was reiterated in the peer-reviewed declaration of a Climate Emergency
64 signed by over 13,000 scientists in late 2019 which highlighted proforestation as a global climate
65 solution (Ripple et al., 2020), as did a recent post on behalf of the International Union for the
66 Conservation of Nature (Kormos et al., 2020). We can use forest-based solutions to rapidly and
67 substantially close the gap between CO₂ emissions and removals by maximizing a range of nature-
68 based solutions (Griscom et al., 2017), and the critical role of protecting intact ecosystems was
69 quantified in a report that documents “wilderness” as reducing species’ extinction by half (Di Marco et
70 al., 2019). Intact forests can simultaneously protect natural selection and biodiversity long-term, reduce
71 extinction, and provide pathways for migration while they continue to accumulate atmospheric CO₂
72 and thereby moderate temperature increases (Friedlingstein et al., 2019). Taken together, it is practical
73 and possible to immediately protect ecosystems and prevent extinction while we increase CDR rates
74 and accumulate additional carbon in forests and forest soils.

75 To date, significant attention has been focused on tropical forests (Mitchard, 2018), yet temperate
76 forests are also biodiverse (Hilmers et al., 2018), benefit human health and well-being in highly

77 populated areas (Karjalainen et al., 2010), and provide many essential ecosystem services (United
78 States Forest Service, 2020a). They also have a large additional potential for CDR (Cook-Patton et al.,
79 2020) and New England Acadian Forests are part of the “Global Safety Net” and recently identified as
80 a Tier 1 climate stabilization area (Dinerstein et al., 2020). Current forest CDR in the United States is
81 estimated to remove an amount of atmospheric CO₂ equal to 11.6% of added annual CO₂ equivalent
82 emissions from the nation’s Greenhouse Gas emissions (United States Environmental Protection
83 Agency, 2020), with the potential for much more (Keeton et al., 2011; Moomaw et al., 2019).
84 Consistent with the IPCC 1.5°C report that identified forests as key to increasing accumulation rates,
85 Houghton and Nassikas estimated that the “current gross carbon sink in forests recovering from
86 harvests and abandoned agriculture to be -4.4 PgC/year, globally” (Houghton and Nassikas, 2018).
87 This potential carbon sink from recovering forests is nearly as large as the gap between anthropogenic
88 emissions and removal rates, -4.9 Pg/year (Friedlingstein et al., 2019).

89 In the context of resource production and forest management, some carbon is stored in lasting wood
90 products, and responsible forestry provides a reliable wood supply. However, a natural forest does not
91 require management, and multiple analyses have found that a majority of carbon removed in a timber
92 harvest is lost to the atmosphere. For example, Hudiburg et al. demonstrated that just 19% of the
93 original carbon stock in Oregon forests in 1900 is in long lived wood products – approximately 16% is
94 in landfills, and the remaining 65% is in the atmosphere as carbon dioxide (Hudiburg et al., 2019);
95 Harmon found that the carbon storage in wood products is overestimated between 2 and 100-fold
96 (Harmon, 2019). Furthermore, Harris et al. has shown that biogenic emissions from harvesting are 640
97 MtC/year, exceeding the commercial and residential building sectors, and fossil fuel emissions from
98 harvesting add an additional 17% CO₂ to the atmosphere (Harris et al., 2016). Strategic planning for
99 responsible resource production can both mitigate these emissions and ensure a protected network of
100 intact natural areas.

101
102 The US Climate Alliance highlights the importance of “net carbon accumulation” in forests across the
103 landscape (United States Climate Alliance, 2020). This is already occurring and demonstrates the
104 power of nature to help us restabilize the climate. A more impactful and explicit goal is to maximize
105 carbon accumulation by utilizing some forests for responsible resource production and protecting other
106 forests for maximal carbon accumulation for climate protection, long-term biodiversity, and human
107 health and well-being. At a global level, if deforestation were halted, and existing secondary forests
108 allowed to continue growing, a network of these intact forests would protect the highest number of
109 species from extinction (Di Marco et al., 2019; World Wildlife Federation, 2020) and it is estimated
110 that they could sequester ~120 PgC in the 84 years between 2016 and 2100 (Houghton and Nassikas,
111 2018). This is equivalent to about 12 years of current global fossil fuel carbon emissions, and these
112 global numbers are conservative as outlined in recent analyses (Cook-Patton et al., 2020) and they do
113 not factor in the enhanced regional CDR potential and high cumulative carbon that can be achieved
114 with proforestation – for example, of carbon-dense temperate forests such as in the Pacific Northwest
115 (Law et al., 2018) and New England (Nunery and Keeton, 2010; Keeton et al., 2011; Moomaw et al.,
116 2019; Dinerstein et al., 2020).

117
118 Because these global and regional projections can be difficult to translate locally, particularly over
119 time, we focused on a detailed analysis of individual trees and stands in New England. Historically,
120 between 80% and 90% of the New England landscape was heavily forested, and early chroniclers
121 describe pre-settlement forests with many large, mature trees reaching 1 to 1.5 m in diameter. Fast-
122 growing riparian species like sycamores and cottonwoods could reach or exceed 2 m. Today, New
123 England trees of this size are mostly found as isolated individuals in open areas, parks, and old estates.
124 Old-growth forests (primary forests) and remnants are currently less than 0.2% of northern New
125 England’s landscape, and less than 0.03% in Southern New England, with ongoing attempts to
126 document their value and identify their locations (Davis, 1996; Kershner and Leverett, 2004; Ruddat,

127 2020). Secondary forests in New England consist mostly of smaller, relatively young trees (less than
128 150 years, and on average less than 100 years old). Without proactive protection, and in the face of
129 programs that almost exclusively incentivize active management (typically for young forests and/or
130 timber production), we risk a future where the vast majority of the landscape will be managed and
131 performing well below its carbon accumulation and biodiversity potential.

132
133 Our goal herein was to measure carbon directly in individual trees and in an “average” versus an older
134 stand of eastern white pine (*Pinus strobus*) in New England. Most forest carbon studies focus on large
135 geographical areas, and utilize “net” carbon data gathered from LIDAR (Light Detection And
136 Ranging) and satellite technology, as well as statistical modeling based on the Forest Inventory and
137 Analysis (United States Forest Service, 2020b) and Carbon On Line Estimator (National Council for
138 Air Stream Improvement, 2020), products of the US Forest Service. We explore these options and note
139 that carbon estimates from different tools and models can lead to disparate results at the level of
140 individual trees – errors that can therefore be extrapolated to stands (Leverett et al., 2020). Therefore,
141 we capitalized on the extensive tree-measuring protocols and experience of the Native Tree Society
142 (NTS) to conduct highly accurate direct field measurements and measure volume precisely in younger
143 vs. older trees growing in stands (Native Tree Society, 2020). We used direct measurements to
144 evaluate volume-biomass models from multiple sources and developed a hybrid – termed FIA-COLE –
145 to capitalize on the strengths of each model.

146
147 For all aspects of this analysis we calculated the live above-ground carbon (in tonnes) in eastern white
148 pines and individuals of other species in a pine stand using conservative assumptions and direct
149 measurements wherever possible and well as direct measurements of individual dominant pines up to
150 190 years in age. Our basic analyses likely apply to other northeastern conifers such as red pines
151 (*Pinus resinosa*), eastern hemlock (*Tsuga canadensis*), and red spruce (*Picea rubens*).

152 153 **2. Materials and methods**

154
155 This paper centers on the study of individual eastern white pines of a representative older stand in
156 Western Massachusetts, collectively named the *Trees of Peace (TOP)* located in Mohawk Trail State
157 Forest, Charlemont, MA. The *TOP* has 76 pines covering 0.6 to 0.7 ha. We also collected and analyzed
158 data from NTS measurements in 38 other sites in the East (Supplement 1). Since 1990, NTS has taken
159 thousands of on-site direct measurements of individual trees in multiple stands of eastern white pines
160 (*Pinus strobus*) (See Supplement 1 for list of sites). Measurements are published on the society’s
161 website (NativeTreeSociety), comprehensive measurement protocols (Leverett et al., 2020) were
162 adopted from those developed by NTS (Leverett et al., 2020) and incorporated into the American
163 Forests Tree Measuring Guidelines Handbook (Leverett and Bertolette, 2014). A brief description of
164 the measurement methods and models is provided in section 2.1, Supplement 2 and (Leverett et al.,
165 2020).

166
167 In the pine stands, a point-centered plot was established with a radius of 35.89 m, covering 0.403
168 hectares (subsequently referred to as 0.4 ha), with the goal of evaluating a standard acre (radius:
169 117.75 ft), and thus relevant to forestry conventions in the U.S. Within the *TOP*, 44 mature white pine
170 stems were tallied along with 20 hardwoods and eastern hemlocks down to a diameter of 10 cm at
171 breast height. The measured acre had 50 pines in July 1989, and since then six trees were lost in a wind
172 event. The pines are ~160 years old, and the hardwoods and hemlocks are estimated to be between 80
173 and 100 years old.

174 175 176 **2.1 Height and diameter direct measurement methodology**

177

178 We quantified the volume of the trunk and limbs of each tree from heights and diameters measured by
179 state-of-the-art laser-based hypsometers, monoculars with range-finding reticles, traditional diameter
180 tapes, and calipers (Leverett et al., 2020). Each high-performance instrument was calibrated and
181 independently tested for accuracy over a wide range of distances and conditions. Absolute accuracies
182 of the two main infrared lasers were verified as +/- 2.5 cm for distance, surpassing the manufacturer's
183 stated accuracy of +/- 4.0 cm. The tilt sensors were accurate to +/- 0.1°, meeting the manufacturer's
184 stated accuracy. The combination of these distance and angle error ranges, along with the best
185 measurement methodology, gave us height accuracies to within 10 to 15 cm on the most distant targets
186 being measured and approximately half that on the closest targets. We distinguished the rated and/or
187 tested accuracy of a particular sensor of an instrument (such as an infrared laser or tilt sensor) from the
188 results of a measurement that utilized multiple sensors.

189
190 Tree heights were measured directly for each pine with a visible top, using the sine method
191 (Supplement 2) whenever possible rather than the traditional tangent method. Our preference for the
192 sine method is supported by NTS, the US Forest Service (Bragg et al., 2011) and American Forests
193 (Leverett and Bertolette, 2014). The more traditional tangent method often over/under-estimates
194 heights by treating the sprig being measured (interpreted as the top), as if it were located vertically
195 over the end of the baseline. The heights of 38 white pines in the *TOP* with visible tops were measured
196 directly using the sine method.

197 198 **2.2 Use of a form factor and FIA-COLE in determining pine volume**

199
200 To compute directly the trunk volume from base to absolute top of a tree, diameters at base and breast
201 height were measured with conventional calibrated tapes according to the procedures established and
202 published by NTS. Diameters aloft were measured with the combination of laser range-finders and
203 high performance monoculars with range-finding reticles. A miniature surveying device, the
204 LTI Trupoint 300, was also used. Its Class II, phase-based laser is rated at an accuracy of +/- 1.0 mm to
205 clear targets. In the *TOP*, we computed the volume of each pine's trunk and limbs using diameter at
206 breast height, full tree height, trunk form, and limb factors. (See Supplement 3 for a discussion on the
207 development of the form factor and its importance in measuring volume, with comparisons to other
208 methods of measurement).

209
210 Detailed measurements of 39 sample trees established an average form factor (see NTS measurements
211 in Supplement 3, Table S3.2). The volume of each sample tree was determined by dividing the trunk
212 into adjacent sections, with the length of each section guided by observed changes in trunk taper and/or
213 visibility. Each section was modeled as the frustum of a regular geometric solid (neiloid, cone, and
214 paraboloid; see Supplement 3 and Leverett et al., 2020, for formulas). Section volumes were added to
215 obtain trunk volume, the form factor was determined needed to equal the trunk volume, given the total
216 height and breast-high diameter of each pine. This produced an average factor that would fit the pines
217 growing in a stand. We applied the average form factor to all pines included in the *TOP* as one
218 determination of trunk volume.

219
220 For comparison to our direct volume measurements, we applied a hybrid volume-biomass model to
221 compute trunk volumes for pines in the *TOP*. This hybrid allowed us to make use of the extensive
222 analysis of the US Forest Service Forest Inventory and Analysis (FIA) program and database (which
223 determines volume and biomass through the use of allometric equations) as well as the Carbon On-
224 Line Estimator (COLE). This hybrid was termed FIA-COLE. See Supplement 4 for a full explanation
225 of the variables and equations for defining trunk volume. We finalized volumes for the pines in the
226 *TOP* by averaging our direct measurements with those of FIA-COLE.

227

228 For the total volume of the above-ground portion of a pine, we derived a factor for limbs, branches,
229 and twigs as a proportion of the trunk volume using the FIA-COLE model (Supplement 5). That model
230 includes all the branching in what is defined as the “top” in a biomass calculation and the limb factor
231 for large trees is typically an additional 15-16%. We ran the model for each of the individuals in the
232 *TOP* and calculated the volume. This was converted to biomass (density) and then to carbon mass
233 using the carbon mass fractional factor.

234

235 **2.3 Analysis of individual pine trees and a representative stand**

236

237 In addition to the *TOP*, and older exemplary pines, we quantified above-ground carbon in younger
238 trees and a representative stand. To determine an “average” pine at 50 years we defined two
239 populations: (1) trees at 50 years that are still alive today, and (2) trees that were alive at 50 years, but
240 are missing today. This allowed us to compute an average trunk size for the missing trees and the
241 associated carbon. We also measured white pines from young to older ages to estimate growth rates
242 and volumes.

243

244 We extensively studied an ~80-year-old stand of pines adjacent to the *TOP* (Supplement 6) growing on
245 a terrace located just downslope from the *TOP* in an area fairly well protected from wind and with
246 adequate soil depth. This age is more representative of the average stand of eastern white pine in New
247 England. We also considered the range of pines of known ages from stands within the vicinity and
248 elsewhere. Where we could, we examined ring growth and height patterns for individual pines during
249 their early years on a variety of sites in different geographical locations. In some cases, we examined
250 stumps and measured the average ring width. In other cases, we measured trees and counted limb
251 whorls to get age estimates.

252

253 We measured the tallest pine in great detail and over a long time-span (referred to as Pine #58, its
254 research tag number). Pine #58 has been measured carefully and regularly over a period of 28 years. In
255 1992 the tree was 47.24 m tall and 2.93 m in circumference. Since then, it has been climbed 4 times,
256 tape-drop-measured, and volume-determined. Pine #58 continues to grow and enabled us to quantify
257 the changes in carbon accumulation in a dominant tree over decades. See Supplement 7 for a detailed
258 measurement history of Pine #58. Additional trees were measured at sites listed in Supplement 1.
259 As noted, above-ground volumes were converted to mass using standard wood density tables (United
260 States Department of Agriculture, 2009). The air-dried density for white pine is 385.3 kg/m³ (0.3853
261 tonnes/m³). We calculated the amount of carbon in each pine using a conservative figure of 48% of
262 total air-dried weight (50% is used more commonly; the percentage of carbon content in different
263 species ranges from ~48% to 52+%). Therefore we calculated a cubic meter of white pine trunk or
264 limbs as holding 0.18494 tonnes of carbon. Note that the carbon in a cubic meter of wood varies
265 depending on the species and is usually higher in hardwoods (United States Department of Agriculture,
266 2009).

267

268

269 **3. Results**

270

271 Using conservative assumptions where needed, and direct measurements wherever possible, we found
272 that individual eastern white pines accumulate significant above-ground volume/carbon at least up to
273 190 years, that this volume/carbon accumulation can accelerate overtime, and that a stand of pines can
274 double its above-ground carbon between ~80 and 160 years.

275

276 **3.1 Analysis of dominant individuals and averages for stand-grown pines**

277

278 As Pine #58 is the tallest and the largest tree (volume) in the *TOP*, its performance over time was
279 analyzed in great detail. It started growing as part of a more tightly packed stand, but presently has
280 ample space. Its circumference at breast height is 3.30 m, its height is 53.64 m, and its crown spread is
281 approximately 15.5 m. Over a period of 26 years, beginning in 1992, Pine #58 has grown in
282 circumference at an average rate of 1.39 cm per year and grown in height 23.71 cm per year. For a
283 chronosequence, we assumed that Pine #58 grew a lot when it was young – an average of up to 61 cm
284 per year in its first 50 years. Its trunk and limb volume was 23.02 m³ at the end of the 2018 growing
285 season (Supplement 7).

286
287 Figure 1 shows the increase in height, circumference and volume of Pine #58 within each 50-year
288 interval up to 150 years. Its estimated age is ~160 years, and we used a chronosequence to determine
289 previous epochs. For dominant pines in stands on good sites, ring widths for the first 50 years average
290 ~0.6 cm and thus a 1.88 m circumference at 50 years. (We measured one exceptional pine at 2.13 m in
291 circumference.) Heights of stands at age 50 depend largely on the site index (the average height of a
292 stand at 50 years), and indices for white pine on good sites usually range from 25.0 to 33.5 m. We used
293 an index near the upper range (30.5 m) and well above the average for Massachusetts to assume rapid
294 early growth. Based on these principles, the change in circumference and growth in height were
295 greatest in the first 50 years, and decreased in the next two 50-year periods, confirming young pines
296 “grow more rapidly” in terms of annual height and radial increases. However, volume growth, and thus
297 carbon accumulation, increased with age. This is primarily because volume increases linearly with
298 height but increases as the square of the diameter (see Figure 1 and Supplement 8).

299
300 As noted, we assumed Pine #58 had optimal rapid growth in the first 50 years. Even so, our analysis
301 supports the conclusion that the pine accumulated the majority of its current carbon *after age 50* and at
302 a slightly increased rate. Pine #58 now stores 4.24 tC above ground and continues to grow. For
303 comparison, the carbon sequestered in the highest volume 50-year-old pine that we encountered (2.13
304 m circumference, 34.75 m height, and 0.4353 form factor) is 1.01 tC. Therefore, even in the best-case
305 scenario Pine #58 would have acquired less than a quarter of its current carbon by age 50.

306
307 The carbon advantage gained by the older trees accelerates with their increasing age and size, a finding
308 that has been affirmed globally (Stephenson et al., 2014). Figure 2 documents the average volume in
309 individual pines in the stands at ~80 and ~160 years as well as several additional large pines. MSF Pine
310 #1, the largest pine in Monroe State Forest, western Massachusetts, has a trunk volume of 35.9 m³ at
311 approximately 190 years (6.15 tC; Figure 2). Assuming its early years accumulated 1.01 tC at 50 years,
312 which is the fastest growing 50-year old pine we measured in all sampled locations, the large pine
313 added 5.14 tC between 50 and 190 years, or 1.84 tC per 50-year cycle after year 50. This is at least
314 1.82 times the rate of growth for the first 50 years. This compares to a 1.6 ratio for Pine #58. In both
315 cases more than 75% of the carbon they sequestered occurred *after* their first 50 years even when
316 assuming the most optimal growth observed during the first 50 years.

317 318 **3.2 Stand measurements at ~80 and ~160 years**

319
320 Detailed measurements were taken in comparable pine stands at ~80 and ~160 years (*TOP*). As noted,
321 the average tree in each stand is shown on Figure 2, and the distribution of tree sizes in the *TOP* is
322 shown in Figure 3A. The largest pine in the *TOP* holds 4.24 tC and the smallest holds 0.53, an eight-
323 fold difference. A comparison of the stand density and above ground carbon at ~80 vs. ~160 yr are
324 shown in Figure 3B.

325
326 Complete data for 76 individual pines in the *TOP* (the 0.4 ha primary plot plus additional trees in the
327 stand) is provided in Supplement 9. For comparison, data from 0.4 ha was collected from an ~80-year
328 old stand growing on a terrace just downslope from the *TOP* in an area fairly well protected from wind

329 and with adequate soil depth (Supplement 6). This age is more representative of the average stand of
330 eastern white pine in New England. Average values for both ages are summarized in Table 1. As
331 shown in Figure 2, we found an average of 0.66 tC per tree compared to 1.95 tC per tree in the *TOP*, a
332 near tripling of carbon in the average individual pine in the older stand. We found a lower stand
333 density in terms of number of stems, and a higher level of carbon in the *TOP*. Pines predominated both
334 plots, and non-pine species added ~10% to the total above ground carbon (Figure 3B).

335
336 We note these calculations only include above ground tree-based carbon – they do not include more
337 labile sources of additional carbon in the needles, leaves and understory plants, or the accumulation of
338 woody debris in older stands. Our measurements also do not include the large store of underground
339 carbon (the root system is typically estimated as an additional 15-20% of the above-ground tree
340 volume, and total soil organic carbon can be an additional 50% or more. Therefore, the total carbon is
341 significantly higher; we do not address those elements here. The above-ground tree-based carbon
342 measured directly in the primary acre in the 80 year old stand is 46.86 tC and the 160-year-old stand is
343 94.4 tC, translating to 117.15 and 236.0 tC per hectare, respectively. Approximately 10% of the tree-
344 based carbon in the older stand is non-pine; non-pine carbon in the younger stand is negligible (Table
345 1).

346 347 **4. Discussion**

348
349 The representative stands in this analysis approximate the average pine forest age (~80 years old) and a
350 comparable stand nearly twice that age. To determine the biomass and above ground carbon in living
351 trees as a function of tree size and age, we have used a combination of direct measurements and a
352 hybrid FIA-COLE volume and biomass model to quantify individual trees and stands of eastern white
353 pine, a common tree species in New England. We found that dominant individual trees accelerate their
354 accumulation of carbon well past 150 years, and more than 75% of the carbon in dominant pines up to
355 190 years is gained after the first 50 years. Despite a lower stand density (fewer stems), total above-
356 ground carbon is greatest in older stands and continues to increase past 150 years. The carbon per
357 hectare quantified in these stands matches previous averages for the region and previous regional
358 estimates that New England forests can accumulate at least twice as much carbon. The total carbon
359 stored is even greater when below-ground carbon in roots, coarse woody debris, standing dead trees
360 and smaller plants and soils are included (Nunery and Keeton, 2010; Tomasso and Leighton, 2014).

361
362 Forest managers stress the high accumulation rates of younger forests as important in absorbing
363 atmospheric CO₂. This is an important consideration for production forests to help optimize between
364 growing a wood resource and accumulating carbon. Younger individual trees do not sequester more
365 carbon than mature trees, and we did not find evidence for a significant benefit for a young stand
366 compared to an older stand but we did not estimate accumulation rates below 80 years. Clearing an
367 older forest to create a young forest creates a large carbon debt. Creating or maintaining this habitat
368 has other benefits (wood production, habitat for hunting, or specific successional species), but it
369 dramatically reduces forest carbon and eliminates the ability for that forest to host the full biodiversity
370 of some of our rarest species of plants, animals, insects, fungi, lichens, reptiles and amphibians found
371 in older and continuously forested areas (McMullin and Wiersma, 2019; Moose et al., 2019) as well as
372 climate-sensitive birds that may benefit from old-growth forests (Betts et al., 2017). These older
373 unmanaged forests also have fewer invasive species (Riitters et al., 2018).

374
375 The pine stands studied here grew from former sheep pastures, therefore not likely starting from a
376 severely disturbed condition and thus minimizing initial carbon elution. This raises the question about
377 the importance of site history in influencing growth, especially in the early years, since a disturbed
378 condition can continue to lose carbon for more than a decade. We recognize that at some point above-
379 ground carbon in living trees will no longer be increasing since the trees eventually die. However total

380 forest carbon continues to increase even in some primary (“old-growth”) forests (Mackey et al., 2015).
381 After tree death or forest disturbance there is a transfer of live carbon to dead wood and woody debris,
382 the litter layer, and into the soil. Here in the older pine stand there is also the increased prevalence and
383 growth of trees of other species (including more carbon-dense hardwoods) so that the species diversity
384 and total carbon load continues to rise. A challenge for future research is to understand tree and stand
385 carbon accumulation and dynamics in detail well beyond 200 years.

386
387 Public forests in New England are typically older than private forests (but still predominantly less than
388 100 years old), and provide the greatest possibility for intact forests across the landscape. Native tree
389 species can live for several hundred years (and in the case of eastern hemlock (*Tsuga canadensis*) and
390 black gum (*Nyssa sylvatica*), up to and exceeding 500 years). Despite the noted lack of old and old-
391 growth forests, and the increasing level of natural disturbances from insects and storms creating forest
392 diversity and forest openings, a major focus on public land is clearcutting to “create young forest” or
393 “create resilience.” These programs assert that young forests prevent a suite of species from declining,
394 that they sequester carbon more rapidly, and that they are more resilient than their older counterparts
395 (Anwar, 2001). This approach has experimental merit, but at this time it needs more direct and long-
396 term measurements and sufficient baselines and controls. It overlooks the dynamic evolution of these
397 habitats over time, creating niches for these species. It also overlooks the critical role of cumulative
398 stored carbon compared to sequestration, and the superior resilience of older forests to the stresses of
399 climate change (Thom et al., 2019). The details of age and location (tropical, temperate, boreal, etc.)
400 are also important in terms of what is reported “young” – in some cases considered up to 140 years
401 (Pugh et al., 2019).

402
403 Our findings are consistent with Stephenson et al (2014) who found that absolute growth increases
404 with tree size for most of 403 tropical and temperate tree species, and a study of 48 forest plots found
405 that in older forests, regardless of geographical location, half of all above-ground biomass (and hence
406 carbon), is stored in the largest 1% of trees as measured by diameter at breast height (Lutz et al., 2018).
407 Keeton et al found an increase in carbon density per hectare as the age of the stand increased in the
408 Northeast U.S. (Keeton et al., 2011) and a recent study in China found that forests with older trees and
409 greater species richness had twice the levels of carbon storage than did less diverse forests with
410 younger trees (Liu et al., 2018). Earlier work demonstrated that intact old growth forests in the Pacific
411 Northwest contained more than twice the amount of sequestered carbon as did those that were
412 harvested on a fixed rotation basis (Harmon et al., 1990). Erb et al. concluded that forests are capable
413 of sequestering twice as much atmospheric carbon as they currently do (Erb et al., 2018). The potential
414 for natural reforestation as a climate solution has just been increased dramatically (Cook-Patton et al.,
415 2020).

416
417 Proforestation - growing existing natural forests - and recognizing the role of older forests and large
418 trees in carbon accumulation and biodiversity protection, are critical components of a global strategy.
419 Rapidly moving large stocks of atmospheric carbon as CO₂ into forests and reducing emissions is
420 essential for limiting the increase in global temperatures, and protecting intact and connected habitat is
421 essential in preventing extinction. An important implication of this finding is that the estimated
422 additional CDR achieved by future growth of secondary forests reported by Houghton and Nassikas is
423 likely an underestimate because it does not account for ongoing accumulation rates as trees age
424 (Houghton and Nassikas, 2018) – at least in regions with relatively young forests like those of the
425 Northeast United States. The global study of natural forest carbon accumulation by Cook-Patton et al.
426 provides quantitative evidence of the power of natural reforestation (Cook-Patton et al., 2020).
427 Considering these reports and the current findings increases the potential regional contribution for
428 increased carbon accumulation rates in the coming decades by Northeastern temperate forests.

429

430 While the IPCC clearly identified forests as essential for sequestering additional carbon for climate
431 stability it focused on production forests that are currently recovering from being harvested or on
432 unforested areas where forests could be planted (afforestation). A report by Bastin et al. proposes
433 massive afforestation on 0.9 billion ha but acknowledges that it will take time before large amounts of
434 carbon would be sequestered (Bastin et al., 2019). Global tree planting efforts are under way but there
435 is little data on how to plant an ecosystem, and some of these tree planting efforts suffer from 75-80%
436 mortality of the young trees. In contrast, growing existing forests that already contain large carbon
437 stores and can rapidly sequester increasing amounts of atmospheric carbon dioxide and accumulate
438 diversity over time - a much more effective near-term and proven strategy (Moomaw et al., 2019).
439 While valuable, neither afforestation nor reforestation will remove as much atmospheric carbon as
440 proforestation in the next 50 years – the timeline when it is needed most to avoid irreversible
441 consequences of a changed climate. Protecting primary forests and secondary forests where possible is
442 also a far better option than the unproven technology of bioenergy with carbon capture and storage
443 (BECCS), also suggested by the IPCC report (Anderson and Peters, 2016; IPCC, 2018). Finally, letting
444 existing secondary forests grow provides equity, natural heritage and cumulative health benefits for
445 people in terms of respite and passive recreation - and does not compete directly with agriculture and
446 other demands for land use.

447
448 The highly accurate direct measurements at the tree and stand level in this paper are consistent with
449 parameterized and other studies at larger scale in verifying that larger trees (Lutz et al, 2018,
450 Stephenson et al, 2014) and stands of larger trees accumulate the most carbon over time compared to
451 smaller trees (Mildrexler et al. 2020). They support the proforestation strategy of growing existing
452 forests to achieve their natural capacity to accumulate carbon and achieve their biodiversity potential
453 (Moomaw et al., 2019) to redress the balance of carbon lost to the atmosphere from global forests
454 (Hudiburg et al., 2020). The important implication of these findings is that the trees and the forests that
455 we need most for carbon storage and CDR to help limit near-term climate change are the ones that are
456 already established.

457
458 Plantations and forests managed for forest products account for 71% of all forest area globally (IPCC,
459 2019), more than sufficient for resource production. Strategic planning can enable some to be
460 prioritized and repurposed for climate protection and research - and the remaining 29% should be
461 protected wherever possible. High levels of carbon accumulation and biodiversity protection can be
462 achieved in parallel with inherent resiliency to a changing climate – including by protecting species
463 networks, genetic diversity and epigenetic changes. These findings also specifically ground-truth the
464 capacity for New England pine forests to more than double their carbon in the coming decades.
465 Protection of public forests from unneeded intervention is urgent, and compensation programs should
466 be established for stewarding private forests based on numerous ecosystem services.

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470
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478
479

480

481 **Author contributions statement**

482

483 RTL chose site locations and individual trees, established measurement methods and protocols, did the
484 on-site tree measuring, and performed the subsequent analysis. SAM analyzed and organized the
485 content and supplements and participated in drafting and finalizing the text. WRM framed the analysis
486 in the context of other studies and the larger context of climate change, assisted with data analysis and
487 presentation, and drafting and editing the text.

488

489 **Conflict of interest statement**

490

491 This work was not carried out in the presence of any personal, professional or financial relationships
492 that could potentially be construed as a conflict of interest.

493

494 **Table 1.** Summary of key measurements within a 160-year pine stand (*TOP*) and a comparable ~80
 495 year old stand (2018 – 2019 values)
 496

Individual Values	<u>~160 year old 0.4 hectare</u>		
	Circumference at breast height (avg)	2.36 m	
	Diameter at breast height (avg)	0.75 m	
	Height (avg)	45.10 m	
	Tree Volume (trunk + limbs; avg)	10.47 m³	
	Above-ground carbon per tree (avg)	1.95 tC	
	<u>~80 year old 0.4 hectare</u>		
	Circumference at breast height (avg)	1.56 m	
	Diameter at breast height (avg)	0.50 m	
	Height (avg)	38.4 m	
	Tree volume (trunk + limbs; avg)	3.58 m³	
	Above-ground carbon per tree (avg)	0.66 tC	
	Stand Values	<u>Full Stand at ~160 years</u>	
		Number of pines	76
Above-ground pine-based carbon		146.84 tC	
Above-ground non-pine carbon		14.90 tC	
Total above-ground tree carbon		161.74 tC	
<u>Research Acre ~160 years (0.4 hectare)</u>			
Number of pines		44	
Above-ground pine-based carbon		85.8 tC	
Above-ground non-pine carbon		8.6 tC	
Total above-ground tree carbon		94.4 tC	
<u>Research Acre ~80 years (0.4 hectare)</u>			
Number of pines		71	
Total above-ground pine-based carbon (negligible non-pine carbon)		46.86 tC	

497

498

499 **Figure Legends**

500

501

502

503 **Figure 1.** Changes in circumference, height and volume of a stand-grown individual eastern white pine
504 (Pine #58) in three 50-y intervals. *Upper panels* - **A:** Change in circumference during 0-50, 50-100 and
505 100-150 y. **B:** Change in height between 0-50, 50-100 and 100-150 y. **C:** Change in above-ground tree
506 volume (trunk plus limbs) between 0-50, 50-100 and 100-150 y. *Lower panels* - **D:** Cumulative
507 circumference at 50, 100 and 150 y compared to cumulative above-ground volume. **E.** Cumulative
508 height at 50, 100 and 150 y compared to cumulative above-ground volume. On each panel initial
509 slopes were matched to reflect the rapid change in circumference and height during the first 50-y
510 interval. Note that volume is a proxy for above-ground carbon. Values for circumference, height and
511 volume of Pine #58 were determined by a combination of direct measurement and chronosequence and
512 described in the text and in Supplement 7.

513

514 **Figure 2.** Tonnes of above-ground carbon (tC) in an “average” eastern white pine in a measured
515 research acre (green locants) and in five individual trees (A,B,C,D,E) measured directly on site at three
516 separate locations in Massachusetts. Average tC and standard deviation is based on pines in a stand at
517 ~80 years (0.66 ± 0.38 tC) and ~160 years (1.95 ± 0.73 tC) as described in the text. Direct
518 measurement of tC is shown for individual trees in western Massachusetts at these ages and locations:
519 A, B - ~190 years (MSF #1 and #2, Monroe State Forest); C - ~160 years (Pine #58, Mohawk Trail
520 State Forest; more details of Pine #58 shown in Figure 1); D - ~150 years (Totem, Northampton, MA);
521 E - ~120 years (BB #2, Broad Brook, Florence, MA).

522

523 **Figure 3.** Carbon distribution, stand density and cumulative carbon in predominantly eastern white pine
524 stands at ~80 and 160 years. These two stands were regrown from land previously used as pasture (i.e.
525 not recovering from a harvest at time zero). **A.** Distribution of above-ground carbon (tC) among 76
526 eastern white pines of different sizes in the full *TOP* stand at ~160 years old. The majority contained 1-
527 3 tC. **B.** Stand density and above-ground carbon measured directly on site in a research acre of eastern
528 white pine at ~80 and 160 years. Stand density (# of stems) declined while above-ground carbon
529 increased. The older stand includes some non-species that added to the number of stem and total
530 carbon (open locants).

531

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