EXEMPLARY FORESTRY FOR CENTRAL AND TRANSITION HARDWOODS

NEW ENGLAND
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FOUNDATION

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Exemplary Forestry for the 21st Century: Managing New England's Central and Transition Hardwood Forest for Bird's Feet and Board Feet at a Landscape Scale

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Introduction

The New England Forestry Foundation (NEFF) has worked for more than 75 years to conserve New England's forests and to promote the highest standards of forest sustainability. In this paper we take a step further and define the characteristics and outcomes of the forestry we strive to practice. We believe these practices will enhance the contributions our managed forests make to mitigating climate change, improving wildlife habitats, protecting biodiversity, and strengthening rural economies. We call this approach to forestry "Exemplary Forestry." NEFF is committed to practicing forestry in line with the standards herein and is offering them to other forest owners who wish to adopt them.

The specifics of what constitutes Exemplary Forestry vary by forest region across New England. The Acadian Forest of northern New England served as an initial focus area to develop this approach in 2018, the results of which are published under separate cover (https://newenglandforestry.org/wp-content/uploads/2021/06/EF-Acadian-Forest-051421-final.pdf). Exemplary Forestry for the Central and Transition Hardwood Forest regions of New England is modeled broadly after the approach adopted for the Acadian Forest but deals with very different wildlife habitats, forest types and silviculture, and climate change mitigation considerations. NEFF intends to hold itself to the standards laid out herein.

A one-page summary of the substance of these standards can be found in Section VI of this paper. The rest of this paper provides the scientific grounding that supports our expectations that this approach will provide the wildlife habitats and climate mitigation, as well as timber production, called for in the 21st century.

Fundamentally, by implementing Exemplary Forestry, NEFF is looking to maintain or enhance the public values that its forests provide, while also supplying materials (wood in its many forms) that are environmentally preferable to non-wood alternatives from several perspectives, including climate change. Realizing financial returns is also important, as achieving reliable financial returns ensures NEFF is able to practice good forestry in the long term. Demonstrating financial viability will also support its efforts to reach other landowners, as well as educate the public about the benefits of long-term forest management for multiple purposes.

NEFF's Exemplary Forestry standards are intended to build on and supplement the good programs already in place to advance beneficial forest practices, such as third-party forest management certification. Of course, and fundamentally important, the Exemplary Forestry paradigm recognizes the importance of keeping working forestland as working forestland, and avoiding land use conversion for uses such as commercial development. Our objective is to concisely define the concept of Exemplary Forestry with a few of the most powerful metrics indicative of good stewardship at the landscape scale in a commercial forestry setting. Beyond protecting the forest environment and the many ecosystem services it provides, Exemplary Forestry is targeted to:

1) Enhance wildlife habitat for the full range of species present;
2) Increase the quality and quantity of both the wood produced and retained in forest stands over time; and
3) Enhance the role forests can play to mitigate climate change—this involves increasing resilience, facilitating adaptation to future climate conditions, and managing forests to sequester more carbon in the forest and in forest products—and to use the other influences of forests on climate change in positive ways as well (e.g., the production of biogenic chemical compounds that can increase the reflectivity of the atmosphere and hence cool the earth).

NEFF's Exemplary Forestry starts from a landscape perspective. To achieve ecological and particularly wildlife habitat goals, the management of any lands must be viewed in the context of the landscape where they occur;

therefore, Exemplary Forestry starts from this broad perspective**.** When forestry is practiced on smaller parcels, such as most of the approximately 150 community forests NEFF owns, we do not expect those parcels to be able to incorporate the full set of specifications identified for Exemplary Forestry on a single parcel (e.g., small parcels cannot include wildlife habitats for a full range of species present in the region). Instead, NEFF's forestry on individual parcels will consider how these lands can maximize their contribution to the landscapes where they occur and help provide as close to the full suite of forest values as possible, by filling in elements missing in the landscape. Sometimes it may require multiple management actions and many years to provide those missing elements.

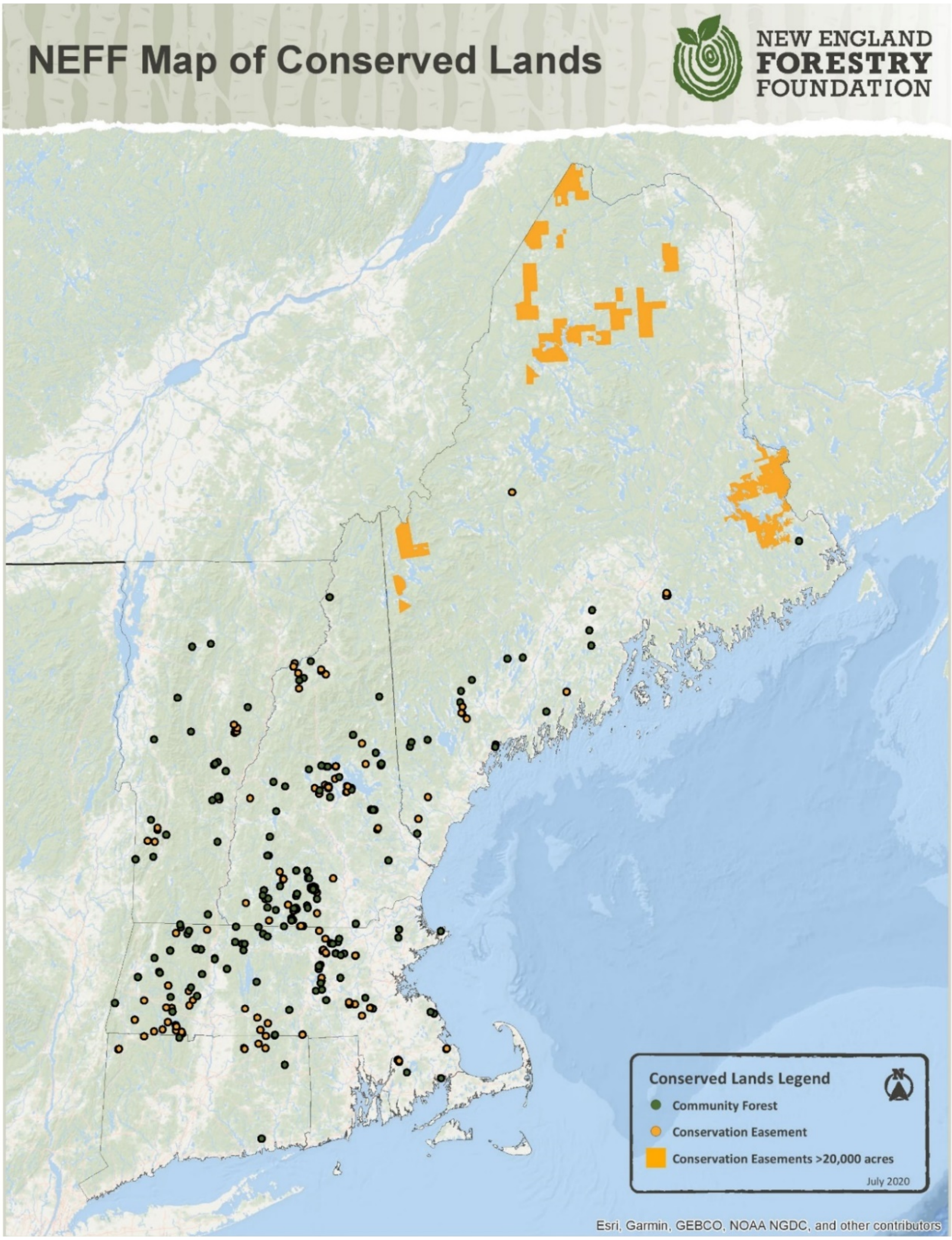
To be clear, these standards are for actively managed forest lands, but NEFF is nevertheless mindful of the important role played by ecological reserves, which a number of organizations, including NEFF, are pursuing. NEFF supports strategically expanding the existing regional system of ecological reserves to meet other habitat needs not met on managed forest lands. As part of this system, NEFF contributes forested parcels it already owns that are designated "forever wild" and not subject to active management.

As stated above, the specifics of what constitutes Exemplary Forestry will vary from one forest region to another. However, across all forest types in New England, Exemplary Forestry aims to manage for landscape scale objectives, including improving the quality of the forest, enhancing wildlife habitat, and mitigating climate change over time by:

1) Growing the tree species best suited to each site;
2) Maintaining or restoring stocking that fully occupies sites in conjunction with regular management to harvest wood products;
3) Growing and harvesting more of the wood our forests are capable of providing;
4) Achieving a diverse stand size class distribution from seedlings to large diameter trees in multi-storied stands;
5) Creating stand conditions that are well suited to the majority of native wildlife species;
6) Employing best management practices to protect soils, riparian habitats, and aquatic habitats, as well as aesthetics;
7) Protecting features recognized as being important for wildlife in most stands (e.g., snags and trees for cavity nesting species), and specialized habitats for species identified as having needs not entirely met by the management outlined above; and
8) Employing a mix of management styles to simultaneously achieve the three goals outlined earlier.

In this regard, NEFF sees Exemplary Forestry as a journey rather than just an end point—that is, practicing Exemplary Forestry means that management puts a parcel on the path to reaching the conditions specified. This approach recognizes that practicing Exemplary Forestry will, in many cases, require decades to achieve the results desired and that disturbances such as windstorms or insects and disease will require finding new paths to the goals.

NEFF Community Forests and Conservation Easement Map



Exemplary Forestry Standards: Central and Transition Hardwoods

The Exemplary Forestry standards are NEFF's guidelines for its actively managed lands. They do not apply to ecological reserves, which NEFF also recognizes as an important component of the landscape and which currently comprise approximately 9% of NEFF's landholdings.[1] These standards, which aim, over the long term, to diversify habitats and maintain approximately half of stands as sawtimber size trees, are intended to be implemented on NEFF's land holdings in the Central and Transition Hardwoods forest types,[2] as shown on the map included. NEFF's management for these lands, its community forests, starts with an assessment of current and anticipated future conditions in the landscape surrounding these properties. We identify which wildlife habitats and critical forest stand structures (defined in the standards herein) are missing or inadequate in the landscape and hence should be emphasized in management planning and execution on NEFF parcels. In addition to implementing these standards, NEFF intends to maintain dual third-party certification of its lands.

Exemplary Forestry in the Central and Transition Hardwoods includes[3]:

1. **Implementing Best Management Practices to protect and improve forest conditions**. Employing accepted "Best Management Practices" to protect soils, riparian and aquatic habitat, special habitats, wildlife trees, and other resources as described in the Exemplary Forestry Best Management Practices (see below and Attachment on this topic).
2. **Implementing advanced silviculture**. Practicing forestry which, over time, results in:
    a. **Continuously improving forest stands** in terms of both quality and quantity.
    b. **Providing conditions which are well-suited to the umbrella wildlife species** known to be representative of the habitat needs of the great majority of native species[4] (see Attachment).

Table 1: Umbrella Wildlife Species by Successional Stage

Successional Stage	Umbrella Wildlife Species	Target Habitat Block Size (in conjunction with meeting stand size class distribution recommendations, see d.)
Interior Forest	Scarlet tanager, Wood thrush, Black-throated blue warbler, tree-dwelling bats (multiple species)[5]	>250-acre blocks of relatively mature, interior forest
Early Successional	Golden-winged warbler, Ruffed grouse, Woodcock, New England cottontail, Blanding's turtle	6–25-acre blocks of early successional forest
Edge and Transition	Red fox, Eastern box turtle, Rose-breasted grosbeak, native bumblebees (Bombus spp.)[6]	Edge and transition stage forest resulting from the above

    c. **Maintaining connectivity** between habitats.

    d. Achieving a **diverse size class distribution** of 5-15% of stands in seedlings[7], 30-40% in saplings and poles, 40-50% in sawtimber and including up to 10% of the landscape in large diameter multi-storied stands.

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[1] The Wildland and Woodlands study by Harvard Forest (Foster, et al. 2005) recommends 10%.

[2] The major forest types in New England's Central and Transition Hardwoods region are oak-pine, oak-hickory, white pine, hemlock, and lowland/riparian hardwood. Where Acadian forest types dominate within the area generally occupied by the Central and Transition Hardwoods, management will be based on the Exemplary Forestry standards for the Acadian Forest and adapted as appropriate for these landscapes.

[3] At the conceptual level these standards parallel those for the Acadian Forest, but, of course, the specifics differ.

[4] These species may change over time as climate changes.

[5] Wide ranging species such as black bear not only require interior forest but also require even larger blocks of undeveloped land.

[6] Habitat studies from the work of State and Federal agencies and numerous organizations and institutions.

[7] Because "natural" disturbances are predicted to increase with climate change, it seems most appropriate to aim for the low end of this range for seedling size stands.

e. **Growing tree species[8] well-suited to each site[9]** (e.g., matched to soil and physiographic conditions as well as expected changes in climatic conditions).

f. **Stocking that fully occupies the sites**; this is an average of "B" line stocking for stands not currently being regenerated.[10] For example, in 8-10 inch diameter stands of mixed wood this would be approximately 20 cords per acre. Adequate regeneration is considered to be 600 seedlings of commercial species per acre.

g. **Growing and harvesting quality timber** at an average of 0.5 cord per acre per year[11].

h. **Addressing climate change** by increasing the resilience to, adaptation for, and mitigation of climate change through forest management.[12] This includes but is not limited to using forests and forest products including products beyond solid wood (e.g., wood fiber insulation) that can store more carbon and substitute for other more carbon-intensive materials like steel and concrete, thereby reducing greenhouse gas emissions.[13] Because many stands in the Central and Transition Hardwoods are heavily stocked, managing to mitigate climate change requires special attention; please see Attachment "Harvesting in Heavily Stocked Stands in Southern New England to Reduce Greenhouse Gas Levels."

i. **Diverse management approaches**. In the long term, NEFF intends to manage significant portions of its properties using both the even-age (regular shelterwood) and multi-aged (irregular shelterwood) management approaches.[14] Different approaches to management are called for to meet the needs of both umbrella and unusual wildlife species[15] and may also be needed to accommodate specific site conditions. For example, the creation of large blocks of early successional habitat by harvesting heavily may be limited to stands that are not heavily stocked, and specific silvicultural practices for oak regeneration and management may be warranted.

j. **Aesthetics.** Public support for forest management, its social license, depends in many cases on how forests look, particularly after harvest. In this regard, NEFF intents to manage its lands to maximize the appeal of managed forests to the public, including but not limited to their visual appeal, particularly in key areas (e.g., attractive roadsides, trails and shorelines). This means harvesting carefully with an eye toward respecting ecological values, avoiding site damage and the appearance of carelessness.[16]

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[8] Decisions of what tree species are "best suited" to each site can be guided by the recommendations contained in soil surveys prepared by the Natural Resources Conservation Service with site conditions verified by a qualified forester or soil scientist. The selection of species should also take into account the changes expected in climatic conditions and their impact on tree growth (Anderson and Palik 2011, USDA NRCS n.d.).

[9] This requires matching the silvicultural system to the site and may require controlling invasive species and/or excessive browsing (Leak 2014, Leak, et al. 2014, Bennett 2010, Rawinski 2014).

[10] 20 cords per acre (Leak et al. 2014).

[11] Harvesting 0.5 cord per acre per year will not be possible on some properties when they are acquired, e.g., if stocking has been greatly reduced. Regarding timber quality, over time the value of the timber should be enhanced (more and better quality sawlogs). Overall, timber volume on NEFF's properties is currently estimated to increase by approximately 2% per year, or 1.25 tons per acre per year (Chris Pryor, pers. comm., 03/26/18). This is approximately 0.5 cord per acre per year depending on species.

[12] USFS guidance on how to increase forest resistance and resilience and facilitate adaptation will be followed.

[13] To understand other ways that forests influence and hence could be used to mitigate climate change, see a PowerPoint NEFF has prepared on this topic.

[14] Because stands in the Central and Transition Hardwoods are commonly fully stocked or overstocked, avoiding potentially significant reductions in carbon stocking in the near term requires phasing the full scope of management specified herein in over time (decades) with light harvesting in the near term. See Attachment "Harvesting in Heavily Stocked Stands in Southern New England to Reduce Greenhouse Gas Levels" referred to in h. above.

[15] For example, in cooperation with the Massachusetts Department of Fish and Game's efforts to recreate a grassland/shrub community for the benefit of certain rare or uncommon species, one NEFF property has been largely converted to an oak savannah and is now on a schedule for controlled burning.

[16] USDA Forest Service. 1995. Landscape aesthetics: A handbook for scenery management. Agriculture Handbook No. 701. 104p.

Exemplary Forestry Best Management Practices

In addition to adhering to the standards of the Forest Stewardship Council and the Sustainable Forestry Initiative, NEFF will employ Best Management Practices (BMPs) to:

a. **Provide wildlife trees** by retaining all snags (if feasible) plus at least 5 live but decaying trees at least 10 inches in diameter per acre (Mass Audubon 2016). At least one quarter of New England wildlife utilize snags for some portion of their life history (DeGraaf et al, 2005), so retention (or creation, when lacking) of a sufficient number of snags throughout time is important.

b. **Protect soils, riparian and aquatic habitats**, including creating and/or maintaining passage for aquatic organisms[17], as well as protection of water temperatures by maintaining canopy cover in riparian zones, designing crossings to minimize impacts to bed and bank of streams, maintaining appropriately sized buffers on surface waters and wetlands.

c. **Maintain soil productivity** by, among other measures, retaining adequate amounts of slash onsite consistent with BMPs developed by the Forest Guild (Forest Guild Biomass Working Group 2010) and complying with applicable guidelines for the timing of operations and types of logging equipment to avoid soil compaction and rutting.

d. **Protect special habitats** including habitats of species identified as having special function, value, or needs[18] not specifically addressed by the Exemplary Forestry management prescriptions. This protection should also extend to those habitats which are critically important for portions of a species' life history, even for the more common species—for example, deer wintering areas and vernal pools.

e. **Control invasive exotics** so they do not limit biodiversity or interfere with regeneration of trees, shrubs, significant or unique ecological areas or features, and other native flora.

f. **Reduce damage** from over-browsing where it is a problem—e.g., leave patches of dense slash to protect regeneration, and consider efforts to keep wildlife populations below destructive levels.

g. Strictly **limit damage to the residual stand**. Conduct harvest and other management operations carefully and with precision and within a seasonally appropriate timeframe.

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[17] Soils, riparian and aquatic resources to be managed consistent with management guidelines from the Natural Resources Conservation Service, state and local regulations or guidelines, and other sources as available.

[18] As identified by state natural heritage and wildlife management agencies, as well as archaeological sites, heritage sites, unique geologic/hydrologic sites, and significant historic/cultural sites as identified by a State Historic Preservation office.

Overview of Forest Types

The New England Forestry Foundation (NEFF) has developed a set of Exemplary Forestry™ standards for the Central and Transition Hardwoods region of New England. These standards are modeled after those NEFF previously completed for the Acadian Forest region of New England. NEFF's efforts for the Acadian Forest included not only development of the management standards, but also analysis of the anticipated results of those standards, and an assessment of the climate change mitigation and associated financial opportunities from implementing them. We have done some of this same work for the Central and Transition hardwoods but intend to do more.

Initiating the Central and Transition Hardwoods Exemplary Forestry project has required NEFF to identify the major forest types to address in the forest management standards for the region.

NEFF utilized a number of resources in determining the dominant forest types for the region's Central and Transition Hardwood forests. The content presented here is intended to be a working draft and subject to change, pending additional information from scientific literature, expert consultation, or through future modeling of silvicultural treatments. The individual silvicultural treatments and prescriptions applicable to each of these forest types are being reported under separate cover and per consultation with the region's silvicultural experts.

The forest types that NEFF has selected for attention in the Central and Transition Hardwoods Exemplary Forestry standards include:

- Oak-Hickory
- White Pine
- Oak-Pine
- Hemlock
- Lowland/Riparian Hardwood

There are, of course, other forest types in the region, but these listed have been selected because they are the most common and economically important in this region. Although Acadian Forest types, including Northern Hardwoods and Spruce-Fir, do occur within the Central and Transition Hardwoods region and may be economically important in some areas, they were excluded from consideration in these standards because they were addressed in NEFF's Exemplary Forestry™ standards for the Acadian Forest region.

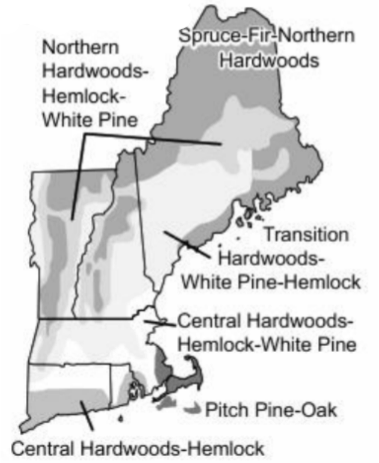

Figure 1. Westveld 1956 map of New England forest types

The forests of New England have been categorized into different types and mapped variously through different studies and publications. NEFF's selection of types has been determined through a review and synthesis of available resources and through consultation with a Technical Advisory Committee. For example:

- Forest types in the New England region as mapped by Westveld on behalf of the Society of American Foresters in 1956 are shown in Figure 1, and are widely cited by others since the map's publication.
- The forest types of New England are similarly mapped by Harvard Forest in their 2010 Woodlands and Wildlands report, as shown in Figure 2.
- The Acadian Forest was mapped by the World Wildlife Fund, which can help in determining the boundary, or approximate boundary/transition into the Central and Transition Hardwoods forest types. The World Wildlife Fund's map is shown in Figure 3.

- Foster (1992) offers another map of New England's forest types that is a somewhat simplified version of the Westveld mapping, included as Figure 4.

Figure 2. Harvard Forest mapping for forest types in New England

Figure 3. World Wildlife Fund mapping of the Acadian Forest in New England

NEFF has chosen to use the Foster (1992) map as the most appropriate for these purposes.

Similar to the variation in mapping forest types, there is also variation in defining and categorizing the regional forest types. For example:

- In New Hampshire, the following forest types are recognized by the New Hampshire Division of Forests and Land:
  - White Pine
  - Northern Hardwood
  - Spruce-Fir
  - Red Oak
  - Hemlock
  - Aspen-Birch

- The Massachusetts Bureau of Forest Fire Control and Forestry names the following forest types in the state:
    - Northern Hardwood
    - Oak-Hickory
    - White and Red Pine
    - Mixed Oak-White Pine
    - Elm-Ash-Maple
- Vermont's Department of Forests, Parks and Recreation notes the following forest stand types:
    - Aspen-Birch
    - White/Red Pine
    - Northern Hardwoods
    - Spruce Fir
    - Other (Oak-Pine, Oak-Hickory, Elm-Ash-Red Maple)
- In Maine, the U.S. Forest Service describes Maine's forest using the dominant forest type groups:
    - Aspen-Birch
    - Spruce-Fir
    - White/Red/Jack Pine
    - Maple-Beech-Birch

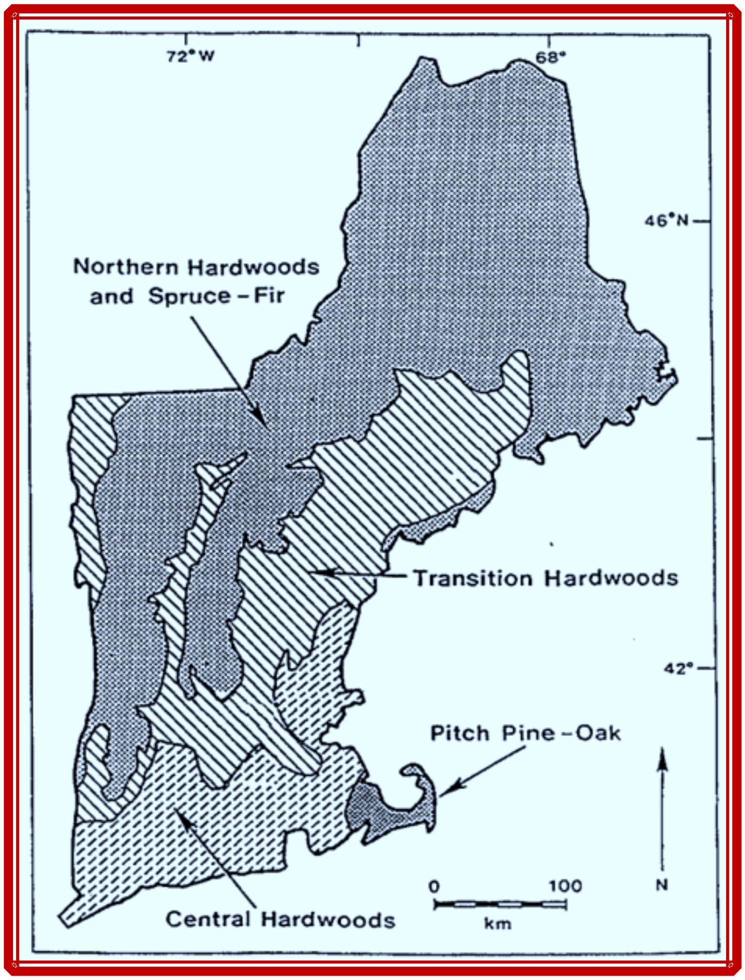

Figure 4. Forest type mapping per Foster (1992)

As is evident from the points above, there are distinctions and overlap between the forest types commonly referenced per state throughout New England. Again, while there are other types present, NEFF's standards for Exemplary Forestry in the Acadian Forest address the dominant types—Northern Hardwoods, Spruce-Fir, and mixed wood forest types. Similarly, NEFF has concluded that the Oak-Hickory, White Pine, Oak-Pine, Hemlock, and Lowland/Riparian Hardwood types encompass the forest types that are dominant in the Central and Transition Hardwoods region of New England and are reasonable type distinctions when considering silvicultural management and associated habitat characteristics. Further, NEFF proposes that the five forest types of Oak-Hickory, White Pine, Oak-Pine, Hemlock, and Lowland/Riparian Hardwood, when combined with the previous Acadian Exemplary Forestry study, will address the primary forest types representative of New England's forests in the context of the development, analysis, and implementation of Exemplary Forestry.

Umbrella Wildlife Species Selection Summary

Introduction

The New England Forestry Foundation (NEFF) has undertaken efforts to enhance forest productivity, habitat conservation, and climate mitigation on lands that it owns in New England's forests. This portion of the New England-wide effort deals with the forests of southern and portions of central New England, and is entitled, "Exemplary Forestry for the Central and Transition Hardwoods" (Project). It is a companion to a previous project completed by NEFF, which was an Exemplary Forestry study for the Acadian Forest region, focusing on the Spruce-Fir and Northern Hardwoods forest types in Maine. The information, results, and opportunities identified in the Acadian Forest Exemplary Forestry work are being used as a foundation to expand the work into the Central and Transition Hardwood forest types.

The contents of this memorandum have been composed by NEFF staff using a number of technical references and peer reviewed publications. NEFF's selection and analysis of suitable wildlife species, as well as other technical and written materials, involved consultation with a multi-disciplinary technical advisory committee. This Draft has been developed for review with the Project's technical advisors after incorporating two rounds of comments. A full record of resources, citations, and advisors on the Project will be included in subsequent papers and/or publications.

The purpose of this memorandum is to introduce and summarize the species that have been determined to be potential umbrella species[19] for the forest types of the Central and Transition Hardwoods forests of New England. As described above, one of the primary objectives of Exemplary Forestry is to conserve and/or enhance habitat for wildlife on working (actively managed) forest land. By using umbrella wildlife species, NEFF's standards for Exemplary Forestry will benefit many species beyond the umbrella species themselves. While developing Exemplary Forestry standards for the Acadian Forest, as reported in *Exemplary Forestry for the 21st Century: Managing the Acadian Forest for Bird's Feet and Board Feet at a Landscape Scale* (NEFF, 2018 and revised in 2019), the Canada lynx and American marten were used as umbrella species and this selection was largely informed by the research findings of biologists from the University of Maine, which was targeted specifically at identifying such species. The study concluded that by meeting the habitat needs of Canada lynx on approximately 27 percent of the landscape and American marten on 16 percent of the landscape, the needs of approximately 84 percent of other native vertebrate wildlife in the area would also be served.

Selecting umbrella wildlife species for the Central and Transition Hardwood forests of New England is more challenging because current scientific literature applicable to the geographic range of the Central and Transition Hardwoods does not provide conclusive data that identify the "ideal" umbrella species.[20]

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[19] Species with habitat needs that serve the needs of many other species as well.

[20] According to NEFF's review of peer-reviewed journals, information available through academic institutions, and studies done by other organizations to date. Further review of additional resources may inform a change.

Umbrella Species and Habitats

Three major habitat types representing forest successional stages are considered to be appropriate foci for this effort to meet the needs of most wildlife species—these are mature forests, early successional forests, and forest edges/transition zones. NEFF proposes that the following can be considered as umbrella species for the forest types and successional conditions that are present in the Central and Transition Hardwoods:

- Mature Forest Interior Habitats: Scarlet tanager, Wood thrush, Black-throated blue warbler, Black bear, tree-dwelling bats (multiple species)
- Early Successional/Young Forest Habitats: Golden-winged warbler, Ruffed grouse, Woodcock, New England cottontail, Blanding's turtle
- Forest Edge/Transition Habitats: Red fox, Eastern box turtle, Rose-breasted grosbeak, native bumblebees (*Bombus* spp.)

The use of these broadly defined habitat categories does not ignore the fact that there are many specialized, unique, and more site-specific habitats that also warrant attention, study, and appropriate measures of conservation, protection, and/or management. At the broad scope of this Exemplary Forestry study, the specialized site-specific management decisions are assumed to occur at the finer-scale, individual parcel management level.

The categorization of forest habitats in New England has been done using a number of methods, approaches, and strategies. Examples include forest type/cover, natural community, moisture regime or wetland type, elevation, biophysical region, and more. This study has used broad categories of habitat type according to successional stage, which is closely linked to forest stand structure found in early successional, transition and edge areas, and mature forest interior habitats and is a useful approach when considering treatment alternatives and results in managed forestland. The approach of using successional stages for analyzing wildlife habitat has also been used in many other studies including (but not limited to) those done by researchers from the University of Vermont, University of New Hampshire, the Audubon Society, and the Natural Resources Conservation Service.

This method of habitat categorization is also suitable for this study because successional stage and structure are conditions reflective of managed, working forest landscapes and the intervention of natural disturbance regimes. Natural disturbances and forest management in the Central and Transition Hardwood forests of New England are largely responsible for the existing forest conditions present on the landscape today and will be the primary influences of the future. NEFF's Exemplary Forestry project examines opportunities to improve the practices of forest management on working forestland, and so has selected successional stage as a means of categorizing wildlife habitats.

- Early Successional: Early successional and young forest habitat, as considered in forest regeneration either by natural disturbance or management, is characterized by young woody plants in a seedling or sapling size and age class. Unless specifically managed to regenerate other species, early successional forests generally have a high proportion of shade intolerant, pioneer tree species and a number of woody shrub species growing densely in areas exposed to full sunlight. Woody plant cover can be so dense that travel and/or predation by large mammals and birds is diminished due to low ground visibility or physical obstruction. For the purposes of being inclusive of a wide range of species with early successional habitat requirements, a patch size of at least 6 acres, and up to 25 acres is recommended.

- Edge and Transitional Stage: Forest edge habitat which exists on the margins of more mature forests is characterized by a diverse mix of woody plants, both in terms of structural/height diversity as well as association with successional stage (post-disturbance colonizers as well as shade tolerant, mature forest species). The transition zone (geographical) or stage (temporal), between an early successional forest and a maturing/mature forest generally includes important food sources for many wildlife species including a diversity of flowering woody plants. In general, the patch size of transition and edge forest conditions will be variable. An area of at least approximately 1 acre or more with diverse vertical height structure and the presence of flowering species is suitable as a food source for many wildlife species dependent on this successional stage for some part of their life history. The scientific literature is not definitive regarding the configuration, or size and distance between patches of this habitat; however, it is clear that having edge and transitional forest within the mosaic of the managed forest landscape serves the needs of a number of species. The amount of such habitat can be increased by managing to create early successional patches, with irregular shapes, within more mature stands.
- Mature Forest Interior: Dense canopy cover of trees (overall greater than 80 percent aerial coverage), potentially with regeneration in the understory and a midstory of advanced regeneration. These stands can include a variety of stand structures, both “horizontal” and “vertical,” e.g., structural diversity of seedlings, saplings, and smaller trees in the understory and advance regeneration in forest gaps left from either natural disturbance or management. Species composition creating the habitat structure is largely comprised of shade tolerant and semi-tolerant woody plants. The minimum block size associated with the scarlet tanager as an umbrella species for this habitat type is approximately 250 acres, with generally blocky dimensional configuration that maximizes the core habitat (rather than narrow or linear configuration with lots of edge).

Assessment Methodology

NEFF’s approach in coming to the above proposed umbrella species assemblages has included several steps which are outlined below. It is notable that additional analysis, including consultation with expert biologists and ecologists in the region, is ongoing.

- Distinguishing general categories of habitat conditions that are present in the region’s forest types, based on current forest and other land management practices and patterns of development. The three general condition categories for forest habitat conditions are Early Successional, Mature Forest Interior, and Edge/Transition. These conditions were then used during NEFF’s literature review to associate individual species with their life history and habitat needs in one or more categories.
- Discussion of preliminary considerations regarding candidate umbrella species with the Exemplary Forestry Advisory Committee, a cross-disciplinary panel of 14 forest and environmental professionals in New England on February 6, 2020 and October 16, 2020.
- Extensive literature review of articles and other publications from a range of sources (all resources included in a bibliography accompanying the final report on Exemplary Forestry for the Central and Transition Hardwoods). Sources include:
    - Scientific, peer-reviewed journals;
    - Federal agencies such as the US Forest Service and US Fish and Wildlife Service and the Natural Resources Conservation Service;
    - Fish and Wildlife Department and Natural Areas Program (or similar) for each New England state;

  - Not-for-profit organizations such as Audubon, The Nature Conservancy, the Gund Institute, American Forest Foundation, National Wildlife Federation, and more;
  - Public and private universities in each of the New England states and New York, and Extension services where established and applicable;
  - Reports and findings from certain private sector projects such as High Branch Conservation Services; and
  - Personal communications, presentation materials, and professional experience of NEFF's project team.

Results

The Central and Transition Hardwoods forest is a relatively rich temperate ecosystem, with many species having known ranges that extend well beyond these forest types and across political boundaries beyond New England. For the purposes of developing standards for Exemplary Forestry that meet the project's objectives, NEFF identified assemblages of umbrella species as well as a subset of "associate species" for each of the forest condition categories (early successional, mature forest interior, edge/transition). Associate species were determined for a number of major taxonomic groups: birds, mammals, plants, reptiles and amphibians, and insects. Detailed tables that present the associate species for Early Successional, Mature Forest Interior, and Edge/Transition habitat types are included in the tables below.

In selecting associate species, NEFF considered:

- Availability of reliable research and/or other studies conducted by more than one source that are not contradictory (i.e., multiple studies must have similar conclusions, rather than one study concluding a certain set of habitat needs and another study with findings that contradict the first);
- Species that are listed as Threatened or Endangered either federally or with rare status in a New England state (RTE), and species that are listed as a Species of Greatest Conservation Need (SGCN) by one or more State Wildlife Action Plans;
- Species that are important to a state and/or the New England region for reasons such as wildlife observation, hunting, recreation, tourism, or of other economic importance;
- Species that are charismatic or otherwise generally recognized or regarded as favorable by the lay public;
- For species with large ranges that extend beyond the Central and Transition Hardwood Forests of New England, either their overall habitat is closely aligned with forests of the region or those forests are important for the connectivity of habitats across the broader range; and
- Inclusion of species across multiple taxonomic groups as a priority.

It is notable that many species require different types of habitat for different parts of their life history; for example, a species that breeds or nests in a forest interior habitat may also need open, early successional areas for foraging. The need for multiple habitats has been addressed in the below summary tables in a general way, however, as the purpose of this study is to broadly encompass forest habitats across large portions of New England. Species have been associated with one of three habitat types (mature forest interior, early successional, and edge/transition forest) according to one or more crucial aspects of that species' life history needs (for example, a necessary food source or patch size for breeding success).

The habitat needs of each umbrella species were compared to those of associate species in terms of size, dimension, and connectivity to other habitat patches on the landscape to ensure that the habitat needs of associate species would be served by those of the umbrella species. NEFF's work on this effort is ongoing, and so there may be revisions to the associate species lists in the future, pending ongoing consultation with biological experts and the availability of more information.

Next Steps

The process for selecting umbrella species assemblages has included consultation with the Project's Advisory Committee as well as consultation with professional biologists and ecologists having expertise in the forest types and/or specific proposed candidate species. As new studies and information become available, the list of umbrella species to guide Exemplary Forestry management may be refined.

Candidate and Selected Umbrella Wildlife Species and Associated Habitat Tables

Table 1 – Proposed Umbrella Wildlife Species

Proposed Umbrella Species	
Early Successional Habitat Candidate Umbrella Species	Golden-winged warbler, Ruffed grouse, Woodcock, New England cottontail, Blanding's turtle
Forest Interior Habitat Candidate Umbrella Species	Scarlet tanager, Wood thrush, Black-throated blue warbler, tree-dwelling bats (multiple species)
Transitional/Edge Habitat Candidate Umbrella Species	Red fox, Eastern box turtle, Rose-breasted grosbeak, native bumblebees (Bombus spp.)

Please note that a number of species are shown as associated with more than one successional stage – this is to be expected for species that depend on different habitat types for different purposes, e.g., they may nest or den in one type but feed in another. However, they may have been selected as an umbrella species for only one habitat type because it is essential to their success.

Table 2 – Analysis of Candidate Umbrella Species – Early Successional Habitats

Early Successional Forest Habitat

A range of Candidate Umbrella Species were initially considered for multiple major taxonomic groups. Habitat requirements for each individual candidate species were analyzed and then proposed umbrella species were proposed based on individual habitat requirements being inclusive of requirements of other candidate species and/or other native wildlife species or groups.

Proposed Assemblage of Umbrella Species: **Golden-winged warbler, Ruffed grouse, Woodcock, New England cottontail, Blanding's turtle**

Species Habitat Associations for Early Successional/Regenerating Forest Structure and Habitat Condition

Reptiles and Amphibians	Plants	Mammals	Birds	Insects/ Pollinators
Eastern box turtle*	Lily-leaved twaybale	Black bear[21]	Blue winged warbler	Karner blue
Eastern hog nosed snake*	Sundial lupine	Moose[5]	Brown thrasher	American burying beetle
Rat snake*	Common Milkweed	Ermine*	**Woodcock***	Frosted elfin
Five-lined skink	Joe-pye weed	*Snowshoe hare*	**Golden-winged warbler**	Dion skipper
Wood turtle*	Raspberries and blackberries (Rubus spp)*	**New England cottontail**	Indigo bunting	Eastern tailed blue
Pickerel frog	Wild senna	Woodland jumping mouse	Hermit thrush	Fritillary butterfly
Spotted turtle*		Little brown bat*	Olive-sided flycatcher	
Blanding's turtle		Eastern small-footed bat*	***Ruffed grouse****	
Smooth green snake		Meadow jumping mouse	Prairie warbler	
Northern black racer		*White tailed deer*[5]	Canada warbler*	
			Eastern towhee	
			Field sparrow	
			Chestnut-sided warbler	
			*Turkey**	

Key To Table

Blue text indicates species that are RTE or SGCN;

Red text indicates species that are charismatic or popularly recognized;

Green text indicates common species notable either as a generalist for habitat suitability, as a keystone species, or for an important predator/prey ecosystem role

Underline indicates that the species also qualifies in another category (i.e., if shown in red text as a charismatic species, the * may indicate it is also a SGCN)

* Asterisk indicates the species has also been associated with another habitat type

Italic text indicates the species is also important for recreation, hunting, tourism, or other similar economic reason

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[21] Wide ranging species such as black bear require large blocks of undeveloped land including a number of habitat types.

Table 3 – Analysis of Candidate Umbrella Species – Mature Forest Interior Habitats

Mature Forest Interior Forest Habitat				
A range of Candidate Umbrella Species were initially considered for multiple major taxonomic groups. Habitat requirements for each individual candidate species were analyzed and then proposed umbrella species were proposed based on individual habitat requirements being inclusive of requirements of other candidate species and/or other native wildlife species or groups.				
Proposed Assemblage of Umbrella Species: **Scarlet tanager, Black-throated blue warbler, Wood thrush, Black bear, tree-dwelling bats (multiple species)**				
Species Habitat Associations for Forest Interior Structure and Habitat Condition				
Reptiles and Amphibians	Plants	Mammals	Birds	Insects/ Pollinators
Jefferson salamander	Wood ferns *(Dryopteris* spp)	**Northern long-eared bat***	**Scarlet Tanager***	Early Hairstreak butterfly
Blue spotted salamander	Pink lady's slipper orchid	**Indiana bat***	**Wood thrush**	
Wood turtle*	Small whorled pogonia	**Little brown bat***	Cerulean warbler	
Eastern box turtle	Large whorled pogonia	**Big brown bat***	**Black throated blue warbler**	
Timber rattlesnake*	American ginseng*	Red squirrel	Blackburnian warbler	
Eastern ratsnake*	Ram's head lady slipper orchid	Southern flying squirrel	Canada warbler*	
Wood frog*	Yellow Lady's slipper	*White tailed deer*[22]	Northern goshawk	
	Trilliums *(Trillium* spp)	Red fox	Veery	
		Bobcat	Pileated woodpecker	
		Black bear[6]	*Ruffed grouse**	
		Long-tailed shrew	*Turkey*	
		Grey squirrel		
		Moose[6]		
Key To Table				
Blue text indicates species that are RTE or SGCN;				
Red text indicates species that are charismatic or popularly recognized;				
Green text indicates common species notable either as a generalist for habitat suitability, as a keystone species, or for an important predator/prey ecosystem role				
Underline indicates that the species also qualifies in another category (i.e., if shown in red text as a charismatic species, the * may indicate it is also a SGCN)				
* Asterisk indicates the species has also been associated with another habitat type				
Italic text indicates the species is also important for recreation, hunting, tourism, or other similar economic reason				

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[22] Wide ranging species such as black bear require large blocks of undeveloped land including a number of habitat types.

Table 4 – Analysis of Candidate Umbrella Species – Edge and Transition Stage Successional Habitats

Forest Edge/Transition Habitat

A range of Candidate Umbrella Species were initially considered for multiple major taxonomic groups. Habitat requirements for each individual candidate species were analyzed and then proposed umbrella species were proposed based on individual habitat requirements being inclusive of requirements of other candidate species and/or other native wildlife species or groups.

Proposed Assemblage of Umbrella Species: **Red fox, Eastern box turtle, Rose-breasted grosbeak, native bumblebees (*Bombus* spp.)**

Species Habitat Associations for Edge/Transition Forest Structure and Habitat Condition

Reptiles and Amphibians	Plants	Mammals	Birds	Insect Pollinators
Eastern hognose snake*	*Elderberry*	Northern long-eared bat*	Least flycatcher	Orange sallow moth
Eastern box turtle*	Arrowwood	Indiana bat*	Eastern phoebe	**Bumblebees (*Bombus spp*)**
Wood turtle	Raspberries and blackberries (Rubus spp)*	Little brown bat	Black-capped chickadee	
Eastern ratsnake*	False foxglove	Big brown bat	Cedar waxwing	
Black racer	Beaked hazelnut	*White tailed deer*[23]	**Rose-breasted grosbeak**	
Wood frog*	Serviceberry	**Red fox**	Baltimore oriole	
Timber rattlesnake*		Ermine*	Purple finch	
		White footed mouse	Great horned owl	
		Eastern chipmunk	Eastern wood pewee	
		Meadow jumping mouse*	White-throated sparrow	
		Meadow vole	*Ruffed grouse**	
			Woodcock*	

Key To Table

Blue text indicates species that are RTE or SGCN;

Red text indicates species that are charismatic or popularly recognized;

Green text indicates common species notable either as a generalist for habitat suitability, as a keystone species, or for an important predator/prey ecosystem role

Underline indicates that the species also qualifies in another category (i.e., if shown in red text as a charismatic species, the * may indicate it is also a SGCN)

* Asterisk indicates the species has also been associated with another habitat type

Italic text indicates the species is also important for recreation, hunting, tourism, or other similar economic reason

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[23] Wide ranging species such as black bear require large blocks of undeveloped land including a number of habitat types.

Parcel-Based Landscape Scale Habitat Assessment Process Outline

The New England Forestry Foundation (NEFF) has developed a set of management standards, called Exemplary Forestry, applicable to the Central and Transition Hardwoods region of New England. The Exemplary Forestry standards aim to achieve three goals: maintain and enhance wildlife habitat at a landscape scale, improve forest productivity, and mitigate climate change by storing carbon both in the forest and in wood products and by substituting wood for other materials that result in greater GHG emissions when they are produced, used, and/or maintained. Although wildlife habitat needs exist at a landscape scale, management decisions for forestry, wildlife, recreation, and other landowner goals are often made only at the scale of an individual parcel. However, to maximize landscape scale benefits, each parcel should be considered in the context of where it is located.

The following outline is intended to summarize the process of analysis NEFF uses in assessing the opportunities provided by existing and potential future wildlife habitat(s) on a given parcel in that context—the surrounding landscape. This outline is intended to be used as a preliminary planning tool, and can be supplemented with other studies, assessments, and information that may be available for any given location or sub-region.

For many wildlife species and communities, it is not only the individual habitat patches or blocks themselves but also their proximity to one another, distribution across the landscape, and the connections between them that are critically important. To maximize the benefits of management for wildlife, individual parcels should be evaluated to assess how their management could contribute most effectively to achieving landscape scale habitat conditions (e.g., those specified in Exemplary Forestry) and how to implement them. For the purposes of this analysis, the surrounding landscape can include the entirety of parcels in the area or only portions of abutting parcels when parcel ownerships are very large (e.g., corporately owned timberland and some public forestland). In other cases, the surrounding landscape may include a radius from the parcel in question and include multiple parcels/ownerships, or may extend up- and downstream along a major landscape feature, e.g., a waterway, ridge, or valley. The purpose of maintaining flexibility in using the term “surrounding landscape” is to include a variety of on-site and area-level conditions and to incorporate the best professional judgment and experience of NEFF’s forestry and ecological experts, partners, and technical advisors.

The process proposed herein is built on the foundation NEFF established through its work on Exemplary Forestry in the Acadian Forest. In 2018, NEFF developed Exemplary Forestry standards for the Acadian Forest region of New England to implement Exemplary Forestry practices effectively across a patchwork of privately owned working forestland in the Acadian Forest. NEFF established a process to inform management decisions that are made at the scale of an individual parcel but take into consideration the existing conditions and habitat objectives for wildlife at the larger landscape scale. The process is already being used in assisting private landowners in implementing Exemplary Forestry in that region.

The process outlined here benefits from that experience but is uniquely designed to accommodate the wildlife habitat diversity, management paradigms, and land development patterns present in New England’s Central and Transition Hardwood Forests. A detailed description of the forest types and wildlife species used as umbrella species for landscape-level planning purposes are described under separate cover. In brief summary, the major forest types that characterize the Central and Transition Hardwoods region of New England include:

- Oak-Hickory;
- White Pine;
- Pine-Oak;

- Eastern Hemlock; and
- Lowland/Riparian Hardwoods.

The umbrella wildlife species being used for Exemplary Forestry in the Central and Transition Hardwoods were chosen as representative of the general forest successional stages, or structural conditions, which occur on managed forestland in the forest types listed above. Umbrella species groups and their associated forest structural condition are:

- Mature Forest Interior Habitats: Scarlet tanager, Wood thrush, Black-throated blue warbler, Black bear, tree-dwelling bats (multiple species);
- Early Successional/Young Forest Habitats: Golden-winged warbler, Ruffed grouse, Woodcock, New England cottontail, Blanding's turtle;
- Forest Edge/Transition Habitats: Red fox, Eastern box turtle, Rose-breasted grosbeak, native bumblebees (*Bombus* spp.).

For more on specific habitat needs, see NEFF's *Umbrella Wildlife Species Selection Summary.*

NEFF's process of parcel-based landscape scale habitat assessment includes the following steps:

1. Evaluate if and what types of habitat or species habitat needs may already exist on site. This evaluation includes consideration of the size and dimensions of the subject parcel, forest conditions, surface waters present, other land cover types on site (field, marsh, high elevation outcrops, etc.), and any direct observation information and/or information from the landowner and/or their forester or other consultants regarding existing habitats or habitat needs.
2. Identify the combination of land ownership types in the surrounding area of the subject parcel. Note that what constitutes the "surrounding area" will differ for different locations. At a minimum, the abutting parcels to the subject site should be included in the assessment. At least a one-mile radius from the subject site is recommended.
    - Publicly owned (includes federal, state, municipal)
    - Non-profit Organization /Institution or similar (includes recreation/tourism-based ownership)
    - Conserved land (any ownership type)
    - Timber Investment Management Organization (TIMO) or other investment-based ownership
    - Paper and Forest Products Industry
    - Private/Family Owned
    - Other (includes energy sector, transportation sector, any other)
3. Based on past performance, define the expected management style for each ownership type in the surrounding area, with special consideration given to the likelihood of maintaining forest land as forest (i.e., not lost to development or other land conversion). Consider factors such as the anticipated type, scale, and frequency of anticipated forest harvests, or if any harvesting is anticipated at all, for each ownership type and how those activities may enhance or diminish habitat conditions on the subject parcel. Note that management can vary significantly within an ownership type (for example in the Federally owned land ownership category, Department of Defense management may differ significantly from the U.S. Fish and Wildlife Service).
    - *Example:* Publicly owned forest land has a negligible risk of development or conversion to another land use compared to privately owned land. Harvesting type, scale, and frequency may

generally be expected to continue as in the past. Management planning on public forestland is generally comprehensive including wildlife, ecology, recreation, and other cultural and environmental values. Forest management planning on public land typically involves stakeholder input and/or other permitting or review mechanism (e.g., National Environmental Policy Act, or NEPA), and so certain best practices and long-term planning objectives are likely to be incorporated.

- *Example:* Land owned by an investment company or a landowner with financial returns as their primary objective may practice even-aged management on a shorter rotation and/or manage for a lightly stocked residual stand followed by overstory removal (rather than retention for legacy or wildlife trees). Because of an emphasis on maximizing financial returns, there may be a higher potential risk of parcelization/development or transition to other ownership type (i.e. non-profit or private family ownership) in the future. Wildlife habitat value may be lower on this type of forest land due to the simplicity of stand structure and age class, and lack of development of structural complexity, accumulation of dead wood, and other late-successional conditions.
- *Example:* Small privately owned land has two trajectories—on the majority of these lands they are simply left to regrow after harvesting that takes the most valuable wood and then harvested again when a financial need arises or the parcel passes from one generation to another. Alternatively, a smaller proportion of these lands receives intensive management carried from generation to generation.

4. Using tax maps or other parcel-mapping resources or information on land ownership, determine the approximate proportion of the surrounding landscape in the various ownership categories described in Step 2 above, and their spatial distribution in relation to the subject parcel.
5. Define expected wildlife habitats that are either maintained, created, or adversely impacted by the dominant management style(s) in the surrounding landscape and how they compare to the desired conditions that are defined in habitat analyses available for the region involved. Resources for such habitat analyses include State Wildlife Action Plans, materials produced by institutions of higher education, regional expert biologists, foresters, and ecologists, and the works of many not-for-profit entities.
    - *Example*: Lands managed extensively to maximize financial returns may contribute to New England cottontail habitat, but may not provide habitat for certain forest interior birds and bats.
6. Analyze data from available databases such as State Natural Heritage Programs, Fish and Wildlife Departments (and other State natural resource and environmental agencies), National Wetlands Inventory, US Fish and Wildlife Service, Web Soil Survey, Regional Planning Commissions, and the many various assessment and planning documents (which will vary by state, county, watershed). This step in the assessment supplements the landownership analysis described in Steps 2 through 5 above. Consider the known, existing biotic and abiotic conditions on the subject parcel and the surrounding area.
    - *Example:* Known Deer Wintering Areas, Significant Natural Communities, rare, threatened or endangered (RTE) species occurrences, wetlands and vernal pools, important wildlife road crossings, etc.
    - Defining known resources will also help to inform management decisions, expected limitations on use, harvest, establishing buffer zones or special treatment areas, or adjusting prescriptions within or near to those resources.

7. Synthesize data from all the steps listed above to determine how to maximize the parcel's contribution to landscape-scale habitat needs given the existing and potential habitat(s) on the parcel involved (e.g., if a given habitat is missing from the landscape and likely to remain so, and if the parcel in question could provide a sizeable, high quality occurrence of that missing type, then a recommendation to manage to provide that habitat would be written into the management plan.

Harvesting in Heavily Stocked Stands in Southern New England to Reduce Greenhouse Gas Levels

Purpose

The purpose of this analysis is to inform the development and execution of NEFF's Exemplary Forestry Standards for the Central and Transition Hardwoods forest of central and southern New England as they apply specifically to heavily stocked stands.

In the development of NEFF's Exemplary Forestry Standards for the Central and Transition Hardwoods forest, the question of how best to manage heavily stocked stands has arisen. Large areas of these forests are indeed heavily stocked and have had limited active management in recent decades; as a result, many of these stands currently store a large amount of carbon. The central question that has arisen is: in light of the large volume of carbon they store, do these stands need special treatment to ensure that management does not reduce their capacity to mitigate climate change in the near term (next several decades)? Or, put another way, what form of management will reduce greenhouse gas (GHG) levels, particularly over the next 30 critical years?

During the development of its Exemplary Forestry Standards for the Acadian forest, NEFF conducted extensive analysis and modeling, which found that broad implementation of those standards would enhance the role of New England's forests in mitigating climate change by storing additional carbon in the forest, while also improving wildlife habitat and enhancing the quantity and quality of wood produced from those forests. We hope to eventually complete a similarly comprehensive and detailed modeling effort to quantify the expected impacts of implementing Exemplary Forestry across the Central and Transition Hardwoods forest of New England. However, in the absence of such a study, NEFF has undertaken this preliminary analysis to estimate the carbon impacts of different types of harvest in high-volume stands in southern New England, in order to assess whether harvesting in these stands can be done in a climate beneficial manner and, if so, how. This analysis is not intended to calculate the precise impacts of each strategy investigated but rather, as a first approximation, to compare relative impacts of types of harvests.

Scope

This analysis estimates the impacts that harvesting following the Exemplary Forestry standards will have on net greenhouse gas emissions over a 30-year period per acre of actively managed forest. Throughout this document, the term "climate beneficial" is used to refer to management that results in *net negative greenhouse gas emissions resulting from forest management and forest product production within 30 years*. This 30-year period is critical for preventing the level of climate change that will produce the most catastrophic consequences for humanity and for forests. Thus, it is important for managers to understand the impacts forest management may have on greenhouse gas balances in this period. However, we understand that the 30-year climate impacts are not the only objective to be considered in forest management decisions.

NEFF and other land managers need to consider and balance multiple goals, including wildlife habitat, financial considerations, and regeneration, among others, along with carbon impacts. In addition, it is important to consider multiple time-related climate goals. The climate crisis will not be resolved in 30 years, and beneficial short-term outcomes need to also consider forest climate impacts over longer terms. We need more science, analysis, and a better understanding of not only short-term outcomes (30 years), but also mid-range (30-75 years), and long-term (75+ years) climate impacts. The current analysis is intended to start that process by understanding the short-term carbon consequences of different management strategies, so that they can be considered and weighed among all the other factors.

Conclusions

The analysis that follows finds that that **a mix of careful thinning to remove the least vigorous trees and small patch irregular shelterwood cuts**, a silvicultural approach likely to be implemented under the Exemplary Forestry Standards for the Central and Transition Hardwoods, **can produce wood in a way that reduces GHG levels within 30 years, even when applied in high-volume stands in southern New England.** When summing carbon storage in the forest, carbon storage in products and landfills, and substitution effects from using wood in place of alternative materials,[24] implementing the silviculture expected under Exemplary Forestry in a heavily stocked (39 cords/acre) 85-year-old oak-pine stand would result in a net climate benefit, equivalent to removing 5-14 MTCO2e/acre from the atmosphere over 30 years.

Limiting harvest in high-volume stands to simply thinning that removes the least vigorous trees would maintain higher carbon stocks in the forest but would also produce less wood. New England currently uses at least 3 million more cords of wood per year than it produces.[25] Given that our preliminary analysis indicates that Exemplary Forestry silviculture, including small gaps as well as thinning, can produce wood in a climate beneficial way and that the climate impacts of wood production elsewhere are unlikely to be uniformly climate beneficial, it makes sense to produce as much wood locally as possible, while also meeting the other goals of Exemplary Forestry.

When compared to business-as-usual (BAU) harvesting practices, Exemplary Forestry silviculture will, on average, increase the amount of carbon maintained in the forest while producing less wood per acre. Thus, to avoid leakage of harvesting and the resulting carbon consequences to other locations where climate beneficial management may not be practiced, active management producing an equivalent amount of wood would need to encompass a somewhat larger area under Exemplary Forestry, compared with BAU management. Producing an equivalent amount of wood to what is produced under BAU management would require approximately 38% more land to be actively managed under Exemplary Forestry silviculture. However, this would still result in less than 1% of forest land being harvested in an average year, and that land would retain more carbon per acre, on average, than land harvested under BAU.

Given that Exemplary Forestry allows for climate beneficial management even in heavily stocked stands, expanding Exemplary Forestry management to an even larger share of the Central and Transition Hardwoods forest (beyond what is needed to replace the wood currently harvested in this region) could result in additional climate benefit by displacing harvest elsewhere that is, in general, likely to have negative GHG impacts. In this analysis, approximately 16 cords/acre would be harvested over 30 years under the Exemplary Forestry management scenario, while also producing a climate benefit.

Thus, implementing Exemplary Forestry on as wide a scale as possible is expected to be carbon beneficial (reducing GHG levels), in addition to providing wildlife and other benefits. Note that this does not mean that every acre of forest should be actively managed, since strategically designated, passively managed ecological reserves are a key component of Exemplary Forestry.

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[24] Studies of the greenhouse gas impacts of substituting wood for alternative materials typically do not take into account the changes in carbon stored in the forest, and may not account for the carbon stored in wood products (in use or in landfill), but it is necessary to account for all of these carbon flows to accurately assess the impacts of timber harvesting.

[25] This estimate, from Ten Broeck (2014) is about 10 years old and should be updated.

Background

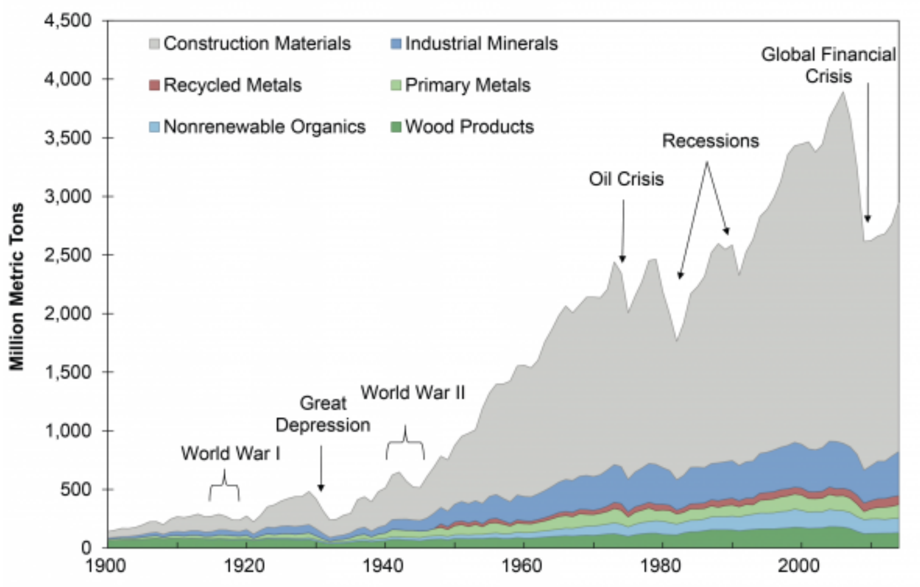
Climate change is increasingly recognized as an existential threat to humanity and civilization:

> *"Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems." (IPCC 2014)*

There is widespread consensus that drastic cuts in emissions of greenhouse gases are needed by 2050 to avoid the most severe impacts of climate change (IPCC 2019). Forests are recognized as playing a significant role in mitigating climate change. Forests store more carbon than is contained in the atmosphere and annually sequester about 11% of anthropogenic CO2 emissions in the U.S. and about 30% of emissions globally (Pan et al. 2011, EPA 2017). When considering how best to manage New England's forests, mitigating climate change, particularly over the next 30 years, must be a primary consideration.

At the same time, demand for raw materials has risen steadily in the U.S. over the last century (except during economic downturns), as shown in Figure 1.

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



[26]

Source: Matos 2017

Continued increases in demand for raw materials will be met either through increased timber harvest or use of alternative (non-wood) materials. As shown in Figure 2 below, the greenhouse gas emissions from producing typical alternative construction materials tend to be substantially higher than those from producing wood products, which leads to potential emission reductions when wood is substituted for other construction materials.

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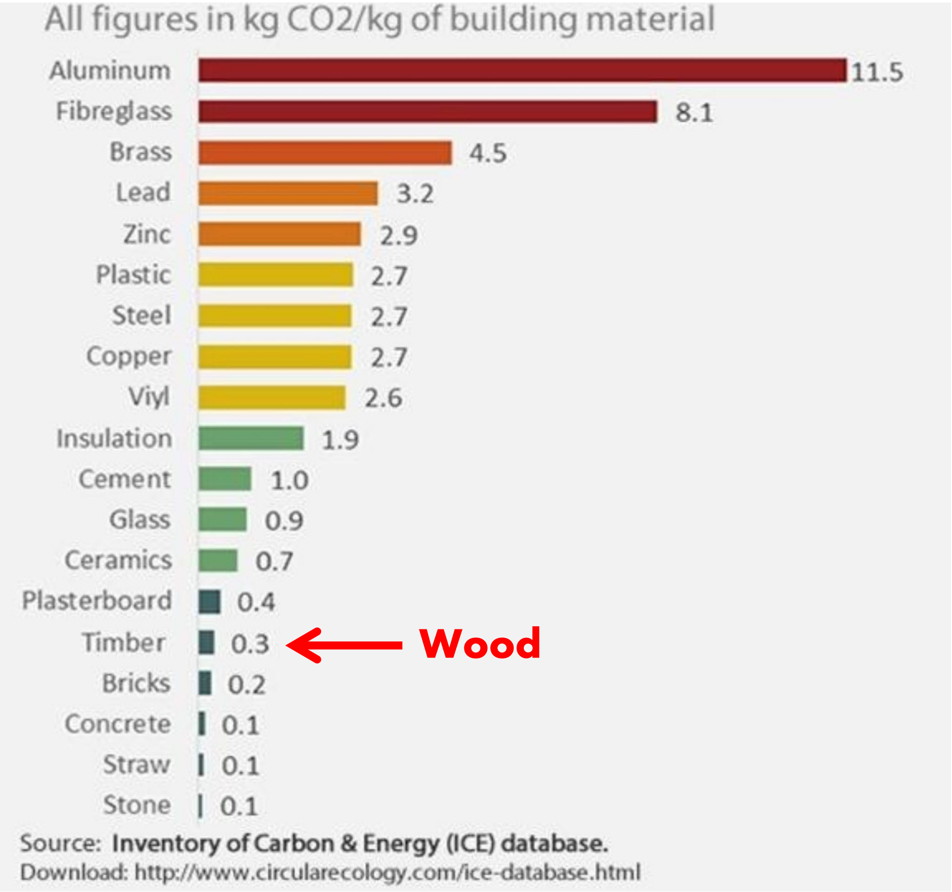
[26] This graph shows raw materials only, measured by weight. "Construction materials" includes sand, gravel, and crushed stone (including those used to make concrete). "Wood products" includes all forest products. "Nonrenewable organics" includes all fossil fuels used for any purpose.

Figure 2. Greenhouse gas emissions from producing building materials



Source: **Inventory of Carbon & Energy (ICE) database.**
Download: http://www.circularecology.com/ice-database.html

Most studies comparing the climate impacts of using wood versus non-wood materials have confirmed that using wood products results in lower greenhouse gas emissions. In a 2018 review of 51 studies comparing 433 pairs of products, Leskinen et al. (2018) reported that the "large majority of studies" indicate that use of wood products results in fewer greenhouse gas emissions than use of functionally equivalent non-wood products.

Further, recent analyses have shown that active management of forests, combined with production of long-lived wood products, has the potential to mitigate climate change more than passive management. Matthews et al. (2014) found that harvesting and using wood products had the potential to sequester up to nearly twice as much carbon per year as a no-harvest scenario over a 20-year time horizon. In a global analysis, Oliver, et al. (2014) also found that "more CO_2 can be sequestered synergistically in the products or wood energy and landscape together than in the unharvested landscape," with the greatest benefits coming from avoided emissions through efficient substitution of wood for concrete and steel. Though the optimal balance of carbon storage in forests and products will vary by local conditions, these findings are consistent with the conclusion that the sustained yield production of wood is typically more beneficial than stopping harvest. Simply put, stopping harvests[27] is typically not beneficial from the perspective of reducing GHG levels, as non-harvest in one location simply shifts harvest to another location where the impacts may be greater (Berlik et al. 2002).

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[27] This does not mean that all forests should be harvested. Ecological reserves are needed for a variety of reasons, such as serving as refugia for species that require late-successional habitat, informing the public about "natural" processes, offering

The Current Situation in the Central and Transition Hardwoods Forest of Southern New England

To understand the potential of harvesting to reduce GHG levels in the Central and Transition Hardwoods forest, it is important to understand the forest's current condition and management. This forest is generally heavily stocked and stores substantial amounts of carbon, compared with the Acadian forest of northern New England. For example, Massachusetts forest land has an average of 31 cords of merchantable volume of growing stock per acre, and stores approximately 200 MTCO2e per acre (excluding soil carbon), per the most recent (2017) FIA data.

Many of these lands are not actively managed for timber production. Based on information from Forest Cutting Plans filed by landowners with the Massachusetts Bureau of Forestry[28], approximately 0.65% of the forested area of Massachusetts is harvested in any given year (VanDoren, pers. comm. 2021). The harvests break down by type as follows:

- Selection (typically small gaps of +/- 0.3 acres with thinnings between gaps), 38%
- Shelterwood (using a variety of systems and cutting intensities), 24%
- Thinning, 14%
- Clearcut/seed tree, 7%
- Diameter limit, 4%
- Salvage/pre-salvage, 4%
- Other (typical removal of +/-66% biomass/basal area), 9%

Assuming that these harvests are representative of BAU harvesting practices in heavily stocked stands[29] in the Central and Transition Hardwoods forest of southern New England, it is noteworthy that 38% of the harvests involve small gaps with thinning between, similar to the silviculture modeled in this analysis, and another 14% are improvement thinnings, similar to the thinning-only scenario analyzed below. Therefore, less than half of the planned harvests would be expected to produce more wood per acre than the Exemplary Forestry harvesting practices modeled in this analysis during the 30-year period. See Supplemental Analysis G for estimates of the wood volume that would be produced under BAU harvesting practices in a heavily stocked oak-pine stand in southern New England.

Definitions, assumptions, and limitations of this analysis

This analysis uses straightforward methods and available data to generate a rough estimate of the climate impacts of harvesting in heavily stocked stands in the Central and Transition Hardwoods forest of New England.

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people opportunities for wilderness experiences, serving as reservoirs of genetic diversity within tree species, and providing scientific benchmarks for assessing the impacts of climate change and forest management.

[28] In Massachusetts, landowners are required to file a Forest Cutting Plan with the state Bureau of Forestry prior to any harvest removing more than 25 Mbf or 50 cords of wood. Note that actual timber removal amounts are not verified after harvest, and Forest Cutting Plans are only required when the land will remain as forest after harvest. Plans are not required if the harvest is in advance of conversion to development or other land use. These data were compiled by William VanDoren of Massachusetts Bureau of Forestry based on Forest Cutting Plans from approximately 2005-2020 and shared with R. Alec Giffen in 2021.

[29] Landowner filings may not be complete or entirely accurate but they are the data base which is available.

As such, it relies on a number of assumptions and generalized data sources. The methods and reliance on existing data mean that the results are only a first approximation of the carbon impacts of the harvests analyzed. More detailed work will be needed to confirm and refine these conclusions. Pending funding availability, NEFF plans to conduct more detailed modeling using data specific to the region to generate more precise estimates of the impacts of implementing Exemplary Forestry throughout the Central and Transition Hardwoods forest of New England.

Exemplary Forestry silvicultural approach

As discussed in the Standards, Exemplary Forestry calls for a range of silvicultural approaches suited to the specifics of each stand. Both regular and irregular shelterwood systems, along with other silvicultural strategies as needed, may be combined on the landscape in a way that will, among other objectives, increase the quality and quantity of standing timber, increase wood production, mitigate climate change, and produce a target stand size class distribution that will support the full range of native wildlife species. See the Silviculture for Oaks and White Pine in the Central and Transition Hardwoods subsection below for a discussion of some specific strategies that may be used to regenerate oaks and white pine.

However, for the purposes of this analysis, which extends for only 30 years, it was necessary to define a generalized "Exemplary Forestry Silviculture" that would be applied to the hypothetical stand to generate estimates of carbon stocks and flows. The silvicultural system modeled in this analysis has two components, or "building blocks." These are:

> 1) patches of irregular shelterwood harvests, in which all of the merchantable volume, except legacy trees, is removed from small patches of various sizes (from less than 0.5 acres for regeneration of shade-tolerant species to up to 2 acres for regeneration of shade-intolerant species) *and*
>
> 2) light thinning from below, which selectively removes 25-30% of merchantable volume in the least vigorous trees in anticipation of eventual mortality.

For this purpose, "Exemplary Forestry silviculture" in heavily stocked stands was defined as patch cuts of various sizes that together make up approximately 20% of the actively managed area, combined with thinning from below to remove the weakest trees in the area between the patches (the remaining 80% of the actively managed landscape). The combination of creating small patches and thinning would result in average removals of approximately 40% of merchantable volume across the actively managed area. Though the silviculture applied across the real landscape under Exemplary Forestry would vary, we expect that the carbon estimates generated here would not vary greatly from the actual carbon stocks and flows expected in heavily stocked stands under Exemplary Forestry.[30]

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[30] For example, regardless of the gap size needed to regenerate various species or benefit wildlife needing larger patches of early successional forest, we would expect the ratio of gaps to thinning for the whole landscape to be similar to the modeled ratio. Additionally, where it's silviculturally appropriate (e.g., for oak regeneration), there will be a delay between initial regeneration harvest and final overstory removal. For the sake of simplifying the analysis, we assumed all trees were removed from the harvested patches at the time of initial harvest. Though this assumption alters the timing of the carbon transfers related to the final removal, the total flows within the 30-year period would be similar for regular and irregular shelterwood prescriptions.

The standards also recommend that a much smaller portion of the landscape be managed using regular shelterwood techniques to create larger patches (6-20 acres in size) of early successional habitat to serve the needs of certain native wildlife species, such as golden-winged warbler, ruffed grouse, woodcock, New England cottontail, and Blanding's turtle. To moderate the short-term impacts on carbon stored in the forest, this type of management should be directed to portions of the landscape that are not heavily stocked and hence are not part of this analysis.

In sum, this analysis estimates the per-acre impacts on net greenhouse gas emissions over a 30-year period of implementing Exemplary Forestry silviculture as recommended across the actively managed landscape, with small gap irregular shelterwood harvest on 20% of the stand and thinning on the remaining 80%.

Silviculture for Oaks and White Pine in the Central and Transition Hardwoods

The following guidelines for silviculture in the oak and white pine types that generally dominate the landscape in the Central and Transition Hardwood region were developed based on literature reviews, several field trips/training sessions, and a review of this topic with Jeffrey Ward of the Connecticut Experiment Station. The silviculture in other forest types will obviously differ, and silviculture on any particular site, even if it is oak or white pine, needs to take the specific circumstances into account. In the future, NEFF plans to incorporate these guidelines into more detailed and comprehensive recommendations for the implementation of the Exemplary Forestry Standards in the Central and Transition Hardwoods.

Based on the literature, field trips and comments from reviewers, we understand that:

1) Without extraordinary efforts, management for oak may only be successful on sites which are average or poor because of competition from red maple and black birch.

2) The gaps created to regenerate stands by creating openings in the crown cover need to vary in size with tree height. A guiding principle is that the size of the opening should be at least two tree heights; this means at least an acre on good sites and perhaps as small as a quarter of an acre on poor sites. The size of openings may need to be bigger where the browsing pressure by deer is heavy. Of course, where the intent is to create larger gaps for early successional wildlife species the size of the gap would be increased.

3) To ensure adequate regeneration, at least one and perhaps two entries may be needed before overstory removal. To encourage the establishment of seedlings, the first (and if needed) second entries should remove as much of the subcanopy as possible and leave a residual canopy cover of approximately 50%. Initial entries should be undertaken in years with a good seed crop. Initial entries to regenerate white pine should involve scarification of the soil to encourage seedling establishment.

4) Overstory removal should occur when seedlings are 4 to 5 feet high, generally 5-10 years after initial harvest.

5) Stand tending may be necessary, particularly on higher quality sites, to maintain oak regeneration as at least codominants.

6) Thinning between the gaps may be difficult to implement due to the lack of markets for small diameter and low quality material. Hopefully markets for firewood and biomass can be encouraged to make this work possible financially. From a silvicultural perspective, thinning operations should work to reduce the regeneration of red maple by crushing seedlings with equipment during the thinning operations or by other means.

Stand characteristics

For this analysis, an average 85-year-old oak-pine stand, as documented by previously published work (Smith et al. 2006), was selected to represent heavily stocked stands in the Central and Transition Hardwoods forest of New England. This age was chosen because more than 60% of the forest land in southern New England supports stands 71-100 years old, based on 2019 FIA data. Average values for carbon storage for an 85-year-old oak-pine stand established following a clear-cut harvest in the USFS Northeast region, as given in Smith et al., were used as the starting point for this analysis. A stand of this type would have approximately 39 cords/acre of merchantable growing stock, based on average volume given in Smith et al. and using a conversion factor of 85 cu. ft./cord. Methods from Smith et al. were used to estimate pre- and post-harvest carbon in the forest, as well as carbon sequestered via growth of the unharvested stand and regrowth of the harvested stand.

Assumptions

This analysis relied upon a range of simplifying assumptions, including the following.

1. **The mix of wood products generated from thinning would be similar to that produced by a shelterwood harvest, with only the volume of wood differing between the two harvests.** We acknowledge that light harvests would produce a different mix of products, likely including fewer high-value products, but generating an estimate of how the product mix would differ, together with the carbon content, longevity, and fate of those products, was beyond the scope of this project.
2. **Based on existing studies, the stand's growth rate (change in merchantable volume of growing stock) would be the same following a thinning/light harvest as it would be if the stand were not thinned.** This is not to say that the wood produced after thinning would not shift to more valuable trees, but simply that the total volume of growth would not differ. The effects of thinning on growth are highly variable, but several studies in heavily stocked oak stands in southern New England have found that volume growth following thinning or initial shelterwood harvest is similar to that in unharvested stands (Ward and Wikle, 2019; Ward et al., 2005; Ward, 1991) (see Supplemental Analysis B for more details). This assumption is expected to be conservative, as other studies have found thinning from below to increase the growth rate of the residual stand (e.g., Hoover 2019).
3. **Carbon in the forest, in products in use, and in products in landfills before, immediately after, and 30 years after harvest will be similar to estimates calculated for an average oak-pine stand in the Northeast region, as given in Smith et al. (2006), which are based in part on product data from the 1990s.** The species mix, product mix, and market conditions for southern New England today may not precisely align with the averages for the Northeast given in that publication, but modifying them was, again, beyond the scope of this effort.
4. **The stand will not suffer a catastrophic event during the 30-year timeframe of the analysis.** In light of the history of major disturbance events in New England and the future influence of climate change, which will make catastrophic events more likely, this is an optimistic assumption. See the 2021 memo from the Yankee Division of the Society of American Foresters' Working Group on Forest Management and Climate Change for more on this topic (Appendix).
5. **Thinning is not assumed to affect the subsequent mortality rate in the stand.** We do expect that careful thinning could anticipate mortality and, thus, prevent some emissions from decomposition in the

forest by harvesting trees before they would have died anyway. Supplemental Analysis H gives a rough estimate of how this could impact carbon accounting for the stand. However, the mortality rates used in this estimate have a large margin of error. Additionally, the forest carbon estimates in Smith at al. incorporate expected mortality rates, and it was beyond the scope of this analysis to adjust these rates. Thus, for the carbon calculations in this analysis, we *excluded* the expected benefits from avoided mortality. As a result, we expect that this analysis undercounts the true reductions in GHG emissions that are likely to occur from Exemplary Forestry silviculture or thinning alone.

Results

This analysis used the forest and product carbon estimates and methods from Smith, et al. (2006) to predict the impacts of alternative silvicultural approaches in an average 85-year-old oak-pine stand on GHG emissions. The net carbon impacts calculated include:

- carbon in the forest (including all carbon pools except mineral soil)[31] +
- carbon in harvested wood products in use and in landfills +
- avoided emissions from substituting wood products for non-wood alternatives.

See Supplemental Analysis A for the detailed calculations and methods.

When all of these emissions pools are considered, the net carbon impact of practicing Exemplary Forestry silviculture is a reduction in GHG emissions of 4.7 to 14.4 MTCO2e per acre over the 30-year period, compared with the initial conditions. The results are given as a range because the substitution factors used to estimate the avoided emissions from substitution of wood for non-wood products range widely in the literature, as discussed in Supplemental Analysis D.[32]

These results are based on calculations of the GHG impacts of the two building blocks of Exemplary Forestry silviculture—patch cuts and thinning—weighted by the portion of the landscape on which each treatment is applied, as shown in Table 1.

As used here, *positive* values indicate increased carbon storage in wood products and/or forest ecosystems (*climate benefits*) compared with the initial conditions. *Negative* values indicate greater emissions to the atmosphere (*climate harm*). As noted earlier, this analysis is intended to be a rough first estimate of the impacts of management; a more detailed analysis using the Forest Vegetation Simulator (FVS) to model impacts of the different management options is planned, pending future funding availability.

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[31] Mineral soil is excluded because research has not found a clear relationship between forest management practices and soil carbon content, particularly for bole-only harvesting (Hoover 2011, Johnson 2001, James et al. 2021).

[32] A substitution factor is defined as the amount of greenhouse gas emissions that would be avoided if a wood product were produced in place of a functionally equivalent product made from non-wood materials. It is measured in units of carbon emissions avoided per unit of carbon in the wood product (e.g., kg C/kg C). However, noted above, as this does not account for all of the impacts of wood production on greenhouse gas emissions. The total impact is calculated as: [change in carbon in the forest] + [additional carbon stored in products in use and in landfills] + [substitution effects of using wood instead of other materials (including avoided emissions from using wood waste to generate energy)].

Table 1: Carbon impacts and wood production from Exemplary Forestry silviculture (see Appendices for detailed calculation of net carbon impacts)

	Net carbon impacts (positive numbers represent increased carbon storage; negative numbers represent emissions to the atmosphere)	**Volume of growing stock harvested**
	MT CO2e/acre	**Cords/Acre**
Exemplary Forestry		
Patch cuts	-6.7 to -1.9	7.8
Thinning	+11.3 to +16.3	8.0
EF silviculture total	**+4.7 to +14.4**	**15.8**

Non-harvest and leakage

It has been proposed that maintaining forests in an unharvested, passively managed condition is optimal for short-term climate benefits because mature forests both store and sequester substantial amounts of carbon (Moomaw et al. 2019). For comparison, we calculated the GHG impacts of leaving the stand under analysis unharvested. Based on the carbon values presented in Smith et al. (2006), if left unharvested, this stand would store an additional 36 MTCO2e/acre over 30 years. At first glance, this appears more beneficial to the climate than Exemplary Forestry silviculture, or even thinning alone. However, this would either lead to substituting other materials for wood or simply shifting the harvest to some other location. As regards the first, research on comparative levels of emissions has demonstrated that other materials typically result in greater GHG emissions (see Figure 2 and Matthews, et al. 2014; Oliver, et al. 2014, Leskinen, et al. 2018, and others). As regards the second, research on leakage has found that, in the absence of changes in demand, avoided harvest in one location leads to additional harvest in other locations within the region, in other regions of the U.S., or internationally (Murray, et al. 2004; Berlik et al. 2002). Economic studies have found that the market for timber products in the US is national (i.e., reductions in supply in one region affect prices throughout the U.S.; Uri and Boyd 1990) and that restrictions on supply from one region lead to increased supply from other regions, rather than changes in total consumption rates (Wear and Murray 2004).

Because reduced harvest in southern New England will lead to leakage of harvest to other locations, this analysis is focused on comparing forest management approaches that produce wood products. Approaches that maintain carbon in the forest without harvesting wood merely displace the carbon impacts of harvesting to other locations, where climate beneficial management is not assured.

EF compared with BAU management

As discussed above, current BAU management involves harvesting about 0.65% of the landscape per year, in a mix of silvicultural prescriptions. On average, BAU harvesting in heavily stocked stands similar to the one in this analysis would produce an estimated 21.8 cords/acre over a 30-year period.[33] Since Exemplary Forestry silviculture is only projected to produce 15.5 cords/acre, about 38% more actively managed land would be required to produce an equivalent amount of wood under Exemplary Forestry, and thus avoid leakage of harvest to other locations. Under this scenario, the area of forest harvested each year would remain very small (less than 1% of the forested area of southern New England), and much of the harvested area would be managed with a lighter touch (i.e., with more carbon remaining in the forest) compared to BAU management.

If, instead, Exemplary Forestry were expanded over a greater area than needed to simply replace the wood currently produced under BAU management, there is potential for increased harvest in southern New England to displace harvesting in other locations inside or outside New England. Given that the demand for wood in New England currently outstrips supply from within the region and the carbon impacts of imported wood are largely unknown, it seems prudent to produce as much wood as possible from New England forests, outside of ecological reserves, as long as this can be done in a manner that's beneficial to the climate and to wildlife.

EF compared with thinning alone

One question this analysis was designed to address was whether it would be more beneficial for the climate in the short term to limit harvesting in heavily stocked stands to thinning from below only, thus maintaining more carbon in the forest. While on a per-acre basis the results of selective thinning alone are more climate beneficial than patch cutting, as shown in Table 1, less wood is harvested per acre under the thinning method. Patch cuts produce around four times as much wood per acre as thinning from below. This means that managing with thinning alone would require eight acres of land to produce the same amount of wood as five acres managed under Exemplary Forestry silviculture.[34]

Another consideration influencing the likelihood of climate-beneficial timber management is that the timber harvested in patch cuts is almost certain to be of higher quality and more merchantable than that harvested from improvement thinning. Thus, harvesting patches would yield greater financial returns for both the landowner and the logger and supply higher-quality wood for the forest products industry. Creating patches of early successional habitat will also diversify wildlife habitat. Diversifying the wildlife habitats of southern New England is clearly desirable if robust populations of the full range of native wildlife are to be maintained. A key need in this regard is to create more early successional and edge habitats (Bley 2014, DeGraaf and Yamasaki 2003, DeGraaf et al. 2006).

Corroborating independent analysis – Preliminary modeling results from hemlock CLT life cycle analysis

While comprehensive modeling of the impacts of Exemplary Forestry in the Central and Transition Hardwoods forest of New England has yet to be undertaken, modeling of a subset of heavily stocked stands is being

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[33] See Supplemental Analysis G for an explanation of how this estimate was produced.

[34] In five acres managed using the two forms of silviculture included under Exemplary Forestry, one acre of shelterwood patch cuts would produce around 34 MTCO2e in wood products excluding pulp and energy, and thinning the other four acres would produce another 35 MTCO2e, for a total of wood equivalent to 70 MTCO2e (difference in total due to rounding). Producing the equivalent amount of wood products using thinning alone would require eight acres. Alternatively, if those eight acres were managed using the combination of patch cuts and thinning between, wood equivalent to approximately 112 MTCO2e would be harvested. Given that harvest avoided in one location is likely to leak to other locations (Berlik et al. 2002), the amount of wood produced by each harvest type is essential to understanding its true climate impacts.

conducted in support of a life cycle analysis (LCA) of cross-laminated timber that could be produced in a hypothetical plant in Ashburnham, MA, using locally sourced hemlock. This modeling effort uses FIA data from plots with at least 8,000 board feet of sawtimber per acre and at least 50% of merchantable volume in hemlock, located primarily in Massachusetts, southern New Hampshire, and southern Vermont. Though the stands in this modeling exercise are somewhat more heavily stocked and store somewhat more carbon than the oak-pine stand in the analysis described earlier (averaging 282 MTCO2e/acre excluding soil carbon, compared with 237 MTCO2e/acre for the oak-pine stand), they are still representative of heavily stocked stands in the Central and Transition Hardwoods forest of New England. The LCA is still in process, but preliminary modeling results generally align with the results of this analysis in showing that applying Exemplary Forestry silviculture has net carbon benefits even in heavily stocked stands.

The preliminary results from this modeling suggest that, if forest carbon, avoided emissions from substitution, and avoided emissions from using wood waste to produce energy are included, applying Exemplary Forestry silviculture in the modeled hemlock stands could result in removing 5.5 to 44.4 MTCO2e/acre from the atmosphere over 30 years. Methods similar to those used in the oak-pine analysis were used to calculate substitution benefits and avoided emissions from using wood waste to generate energy. The components used to produce this estimate are shown in Table 2.

Table 2: Summary, carbon impacts of Exemplary Forestry silviculture,[35] based on results of FVS modeling conducted for hemlock CLT LCA

	MTCO2e/acre (positive numbers represent increased carbon storage, or climate benefit)	**Notes**
Loss of onsite carbon storage	- 89.2	Based on change in forest carbon between pre-harvest stand and stand 30 years later, after two rounds of thinning and patch cuts. Includes regrowth.
Increase carbon storage in product and landfill	+ 37.7	Based on outputs from preliminary FVS modeling provided by SIG.
Avoided emissions from substituting wood for other materials	+44.4 to +83.3	Based on the carbon in harvested wood products from FVS modeling, and using a substitution factor between 0.8 and 1.5 (see Supplemental Analysis D).[36]
Avoided emissions from using wood waste to produce energy	+12.6	Based on the C from wood products that has been emitted with energy generation through 2051 (per FVS modeling results), net of wood energy used in wood product manufacture, and assuming the wood fuel displaces natural gas.[37]
TOTAL	**+5.5 to +44.4**	This is net storage (or net reductions in emissions to the atmosphere).

Despite the different assumptions used in the two analyses, they produced a similar result: Exemplary Forestry silviculture is likely to produce a small net carbon benefit over 30 years. This provides additional confidence that the results of the current analysis are reliable.

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[35] Note that the Exemplary Forestry silviculture modeled in the hemlock LCA was slightly different from what was applied in the oak-pine analysis. In the hemlock modeling, thinning removed 33% of merchantable volume, compared with just over 25% in the oak-pine analysis. The hemlock modeling also included a second entry at year 20 that created a second set of patch cuts accounting for 20% of the landscape, as well as a second thinning across the remainder of the landscape. In contrast, the oak-pine analysis included only one set of patch cuts and one thinning.

[36] These estimates are for the production-phase substitution factor only. Leskinen et al. broke down substitution factors into four components: those that addressed the difference in greenhouse gas emissions between a wood and non-wood product for the *production* phase of the product (e.g., extraction, processing, and transportation of raw materials, manufacturing of final product), the *use* phase (e.g., emissions created by the use and maintenance of a product), the *cascading* effects (e.g., the impacts of recovery of materials from products at end of life), and the *end-of-life* phase (e.g., when the product is landfilled, burned, or otherwise disposed of). The current analysis includes emissions for the production phase of both wood and non-wood products. The end-of-life phase is included as a separate line item for wood products that are disposed of within the 30-year time frame of the analysis. Very few studies in the Leskinen et al. review included information on the use or cascading effects components of substitution factors, and we also did not find data for these phases in regionally relevant sources, so these phases are not addressed in the current analysis.

[37] The ratio of total emissions with energy generation to energy used in wood product manufacture was assumed to be the same as in the oak-pine stand analysis. See Supplemental Analysis E for detailed methods.

Supplemental Analysis A: Detailed calculations

To estimate the total greenhouse gas impacts of implementing Exemplary Forestry silviculture, we first calculated the per-acre greenhouse gas impacts of the two silvicultural building blocks of Exemplary Forestry:

1) Irregular shelterwood harvests that remove essentially all of the merchantable volume from the harvested patches. The calculations in Table A1 look at *only* the per-acre carbon impacts *in the harvested patches*, not including the areas to be thinned between patches.
2) Harvesting targeted to selectively removing 10 cords/acre (just over 25% of merchantable volume) in the least vigorous trees in anticipation of mortality. The calculations in Table A2 look at *only* the per-acre carbon impacts *in the thinned areas.*

The results shown in Tables A1 and A2 below include five components: loss of in-forest carbon following harvest, increase in carbon stored in wood products in use and in landfills, avoided emissions from substituting wood for non-wood products, avoided emissions from using wood waste instead of fossil fuels to produce energy, and increased carbon storage in the forest due to growth or regrowth over the 30-year period. The methods used to calculate each of these components are detailed in Appendices B, C. D, and E.

Recall that *positive* values here indicate increased carbon storage in wood products and/or forest ecosystems (*climate benefits*) compared with the initial conditions. *Negative* values indicate greater emissions to the atmosphere (*climate harm*).

Table A1: Summary, carbon impacts of patch cuts (per acre of harvested patches only)

	MTCO2e/acre (positive numbers represent increased carbon storage, or climate benefit)	**Notes**
Loss of onsite carbon storage	- 168.9	Based on change in forest carbon between pre-harvest and post-harvest stand from Smith et al. (2006).
Increase carbon storage in product and landfill	+ 32.2	Estimated using methods from Smith et al.[38]
Avoided emissions from substituting wood for other materials	+27.5 to +51.6	Based on the estimated C in wood products (excluding pulp and fuel) following methods in Smith et al., and using a production-phase[39] substitution factor between 0.8 and 1.5 (see Supplemental Analysis D).
Avoided emissions from using wood waste to produce energy	+15.4	Based on the estimated C from wood products that has been emitted with energy generation through year 30 according to Smith et al., net of wood energy used in wood product manufacture, and assuming the wood fuel displaces natural gas.
Regrowth	+ 60.3	Based on change in forest carbon between post-harvest stand and 30-year-old stand from Smith et al.
TOTAL	**-33.4 to -9.3**	These are net emissions to the atmosphere.

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[38] Note that this is likely a conservative estimate for the amount of carbon stored in product and landfills after 30 years, since more recent research has found lower rates of decomposition for landfilled wood products than those assumed in Smith et al. (see Supplemental Analysis F).

[39] As discussed earlier, Leskinen et al. (2018) broke down the substitution factors into four life cycle phases. The current analysis includes emissions for the production phase of both wood and non-wood products. The end-of-life phase is included in separate line items for wood products that are disposed of within the 30-year time frame of the analysis. Very few studies in the Leskinen et al. review included information on the use or cascading effects components of substitution factors, and we also did not find data for these phases in regionally relevant sources, so these phases are not addressed in the current analysis.

Table A2: Summary, carbon impacts of thinning from below targeting the weakest trees (per acre thinned)

	MTCO2e/acre (positive numbers represent increased carbon storage, or climate benefit)	**Notes**
Loss of onsite carbon storage	- 43.4	See Supplemental Analysis B for methods.
Increase carbon storage in product and landfill	+8.3	Assumes proportions of sawtimber vs. poletimber and hardwood vs. softwood harvested wood are the same as in irregular shelterwood.[40]
Avoided emissions from substituting wood for other materials	+7.1 to +13.3	Based on the estimated C in wood products (excluding pulp and fuel) following methods in Smith et al., and using a production-phase substitution factor between 0.8 and 1.5 (see Supplemental Analysis D).
Avoided emissions from using wood waste to produce energy	+4.0	Based on the estimated C from wood products that has been emitted with energy generation through year 30 according to Smith et al., net of wood energy used in wood product manufacture, and assuming the wood fuel displaces natural gas.
Regrowth	+ 38.3	Based on an assumption[41] that growing stock volume would increase at the same rate as in an unharvested stand, as given in Smith et al. (2006), and using the methods in that publication to estimate forest carbon in the resulting stand (see methods for details).
TOTAL	**+ 14.2 to +20.4**	

The carbon impacts of each treatment were weighted by the share of the stand undergoing that treatment (80% for thinning and 20% for patch cuts) to get the overall carbon impacts of applying Exemplary Forestry silviculture. Table A3 shows both greenhouse gas impacts and wood produced per acre for Exemplary Forestry silviculture across the actively managed landscape.

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[40] Note that the mix of harvested wood products is likely to be different, but in the absence of a detailed modeling exercise, no estimate was available for the product mix expected from thinning. We expect that thinning would produce lower quality products, on average, than the irregular shelterwood harvest.

[41] This assumption is based on research by Ward and Wikle (2011), as described in Supplemental Analysis B.

Table A3: Carbon impacts and wood production from Exemplary Forestry silviculture (the combination of patches and thinning from below) across the landscape

	Net carbon impacts (positive numbers represent increased carbon storage; negative numbers represent emissions to the atmosphere)	**Volume of growing stock harvested**
	MT CO2e/acre	Cords/Acre
Exemplary Forestry		
Patch cuts	-6.7 to -1.9	7.8
Thinning	+11.3 to +16.3	8.0
Total	**+4.7 to +14.4**	**15.8**

Supplemental Analysis B: Forest carbon and growth calculations

Smith et al. (2006) presented estimates of carbon per acre for five pools (live tree, standing dead, understory, down dead, and forest floor) for forest type groups by U.S. Forest Service region and stand age, together with detailed methods for estimating carbon in the forest and in harvested wood products. Their estimates for oak-pine stands in the Northeast region were the basis for our calculations of forest carbon and growth, except for the forest floor carbon pool.[42] The data in Smith et al. are for stands generated following clear-cut harvest. Forest carbon values in the harvested patches following the irregular shelterwood harvest in this analysis are expected to be similar, as the irregular shelterwood patch cuts are essentially like multiple miniature clear-cuts, from a carbon perspective.

We used the carbon estimates from Smith et al. for stands at age 0 (immediately following clear-cut harvest), age 30 (using the mean of the estimates for stands aged 25 and 35), age 85, and age 115, converted to MTCO2e/acre. Values for the thinning scenario were calculated following the methods recommended in Smith et al., based on removing 10 cords/acre (about 25% of merchantable volume) via thinning.

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[42] The forest floor estimates in Smith et al. were based on a model by Smith and Heath (2002), but this model was found by Domke et al (2016) to overestimate the forest floor carbon pool across the U.S, when compared with estimates derived from litter samples from FIA plots. As a result, we used estimates for forest floor carbon based on litter samples from Maine FIA plots sampled in 2012-2016, as provided to the Maine Forest Service by Grant Domke in 2018. These estimates ranged from 31% to 77% of the values given in Smith et al. As the forest floor pool is relatively small and changes very little over the time period of this analysis, it does not substantially impact these results.

Table B1: Carbon estimates by pool, stand age, and harvest scenario

Stand	Merchantable volume of growing stock	Live tree	Standing dead	Understory	Down dead	Forest floor	Total
	cords/ac	MT CO2e/ac	MT CO2e/ac	MT CO2e/ac	MT CO2e/ac	MT CO2e/ac	MT CO2e/ac
Existing stand (85-year-old oak-pine)	38.9	197.6	7.0	3.3	12.5	16.7	237.0
Growth of existing stand over 30 years	+8.6	+33.4	+0.4	no change	+1.8	+0.9	+36.4
Patch cut immediately post harvest	0	0	0	6.2	44.4	17.6	68.2
Patch cut 30 years post-harvest	19.4	86.5	5.1	4.2	13.9	18.6	128.4
Thinning (to remove 10 cords/ac), immediately post-harvest	28.9	155.9	6.4	3.5	11.2	16.7	193.7
Thinning, 30 years post-harvest	37.5*	192.1*	6.8*	3.3*	12.2*	17.6*	214.4

* Volume growth following the thinning was assumed to be the same as in the uncut stand, based on results from Ward (2011) and Ward and Wikle (2019), who found that, while the residual trees did respond to thinning with increased growth, total basal area growth for the stand was unchanged or lower in thinned oak stands in the first 11 years post treatment, compared with unthinned controls. Carbon in live and standing dead trees 30 years post-harvest is based on the stand volume predicted from this growth rate, and other carbon pools for this scenario are calculated from the live tree carbon and stand age using the methods recommended in Smith et al. (2006).

The amount of carbon removed from the forest through the irregular shelterwood patch cuts was calculated as the difference between carbon in the age 85 and age 0 stands. Carbon sequestration through growth following the patch cuts was calculated as the difference between carbon in the stand at age 30 and carbon in the stand at age 0. Note that the carbon in [understory] + [down dead] + [forest floor] declines by 31 $MTCO_2e$/acre from age 0-30, so the decomposition of this material is accounted for in the regrowth number, rather than in the number for initial loss of carbon storage.

To estimate carbon lost from the stand in the thinnings, volume equivalent to 10 cords/acre was subtracted from the volume in the 85-year-old stand, and the methods in Smith et al. (2006) were used to produce estimates for the carbon pools based on the new merchantable volume, keeping the stand age at 85. This likely underestimates the carbon in the down dead pool post-harvest, but it was assumed that the down dead pool would return to the expected number for the stand age within the 30-year analysis period (i.e., the limbs and tops would biodegrade within 30 years, so should be counted as emissions for this analysis).

For growth following the thinnings, growing stock volume was projected to increase at the same rate as in an unharvested stand, calculated as the change in volume between stands at age 85 and age 115. This would add 731 cubic feet/acre, or 8.6 cords/acre, to the residual stand over the 30 years. The methods in Smith et al. (2006) were used to generate estimates of carbon in the forest pools after 30 years (at stand age 115), based on the calculated growing stock volume of 37.5 cords/acre. Following the methods in Smith et al., the estimates of carbon in the live tree and standing dead pools are based on growing stock volume, while understory and down dead pools are based on live tree carbon, and the forest floor pool is based on the stand age of 115 years.

The assumption that the total stand growth rate after thinning would be similar to growth in an unharvested stand is based on Ward (2011) and Ward and Wikle (2019), who found that in heavily stocked red oak stands aged 79-125 in Connecticut, neither total basal area growth nor sawtimber growth increased over 11 years following thinning, compared with untreated stands (though crop tree growth did increase, indicating that thinning shifts growth to the residual trees rather than reducing it). We expect that this is a conservative assumption, as other studies have found thinning from below to increase the growth rate and carbon storage of the residual stand (e.g., Hoover 2019, in Allegheny hardwoods).

Supplemental Analysis C: Carbon storage in product

Estimates for carbon stored in product and landfills were derived following the methods in Smith et al. (2006) who provide conversion factors based on regional averages by forest type group to convert from carbon in volume of merchantable growing stock (20.7 MT/acre, or 75.9 MT CO2e/acre) to carbon in industrial roundwood harvested (27.8 MT/acre, or 102.0 MT CO2e/acre[43]) to the disposition of carbon in wood products 30 years after harvest (products in use: 16.3 MT CO2e/acre; products in landfills: 16.0 MT CO2e/acre; products combusted for energy: 37.5 MT CO2e/acre; carbon emitted without energy production: 32.2 MT CO2e/acre). The product disposition estimates are based on averages for products from each specific region of the U.S. For these calculations, the small fraction of products that are exported are treated as though they were used in the U.S.

Note that these product disposition estimates include only the carbon in harvested industrial roundwood, and not that in fuelwood. The product disposition factors are based on average product mix by industrial roundwood category (softwood saw logs, softwood pulpwood, hardwood saw logs, or hardwood pulpwood) and region (based on 2002 data), combined with national averages for end uses of each product category (based on 1998 data) and the half-life of each end use and disposition of each product category (e.g., 30 years after harvest, the fraction of oriented strandboard remaining in use is 0.666, while the fraction in landfill is 0.196, based on 58% of this product category going into new single-family homes with a half-life of 100 years, and so on).

Supplemental Analysis D: Substitution benefits

Regionally specific estimates of the carbon impacts of using harvested wood products instead of non-wood alternatives were not available for the range of products anticipated from the harvest in this analysis. Based on a review of available published substitution factors and the product mix predicted from this harvest using the

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[43] Note that the carbon in industrial roundwood harvested is greater than the carbon in merchantable growing stock because some of the harvest is from non-growing-stock trees.

methods from Smith et al. (2006), we believe that a production-phase substitution factor between 0.8 and 1.5 is appropriate for this analysis.

The production-phase substitution factor is based on estimates from two sources: an average substitution factor of 0.8 from a comprehensive review by Leskinen et al. (2018), and a range of 1.0-1.5 calculated based on estimated emissions for several product types produced from northeastern forests, weighted by the mix of hardwood and softwoods predicted from this harvest.

To estimate the carbon impacts of using harvested wood products instead of non-wood alternatives, we searched for studies that calculated substitution factors for the types of wood products likely to be produced from the harvests in the current analysis. A substitution factor is an estimate of the relative benefit of using a wood product compared with a non-wood alternative that serves the same purpose. Substitution factors are typically expressed as unitless ratios of the mass of carbon emissions avoided per mass of carbon in the wood product being analyzed (for example, kg CO2e/kg CO2e). Leskinen et al. (2018) broke down the substitution factors into four components: those that addressed the difference in greenhouse gas emissions between a wood and non-wood product for the *production* phase of the product (e.g., extraction, processing, and transportation of raw materials, manufacturing of final product), the *use* phase (e.g., emissions created by the use and maintenance of a product), the *cascading* effects (e.g., the impacts of recovery of materials from products at end of life), and the *end-of-life* phase (e.g., when the product is landfilled, burned, or otherwise disposed of).

The current analysis includes only production-phase substitution effects. Very few studies in the Leskinen et al. review included information on the use or cascading effects components of substitution factors, and we also did not find data for these phases in regionally relevant sources, so these phases are not addressed in this current analysis. The end-of-life phase was also excluded, since energy recapture from wood products at end of life is calculated as a separate line item using estimates of emissions with energy capture from Smith, et al. (2006). It was not possible to determine what, if any, end-of-life impacts from non-wood materials would occur within the 30-year timeframe. It is expected that most non-wood materials would either last beyond the 30-year timeframe of the analysis or be landfilled, resulting in little impact on greenhouse gas emissions during this period.

Studies estimating substitution effects for wood harvested from this region and forest type were limited. Since no studies were available to give specific estimates of substitution benefits for the product mix most likely to be produced from this harvest, two different methods of estimating these benefits were used.

First, the average substitution factor was identified from the most comprehensive review of the topic to date, by Leskinen et al. (2018). This review, which included 433 substitution factors from 51 studies, reported the average production-phase substitution factor as 0.8. There are several concerns with using this average in the current analysis. First, this average includes substitution factors from studies encompassing a wide range of geographies, products, assumptions, and methodologies, many of which are not applicable to this region or to the timeframe of this analysis. In addition, the specific substitution factors reported varied widely depending on the specific products compared, and it is not clear which comparisons would be most relevant to the current analysis. Still, in the absence of sources specific to this region and product mix, using an average seemed a reasonable approach.

The second method for estimating substitution benefits used results from Bergman et al. (2013) to produce cradle-to-gate estimates for the emissions generated by harvesting and processing wood products sourced from the northeastern U.S. and selected non-wood alternatives. The products identified as most relevant from this study were hardwood and softwood lumber, solid wood flooring, and solid wood doors. The non-wood substitutes evaluated were PVC molding for hardwood lumber, steel studs for softwood lumber, vinyl flooring for solid wood flooring, and steel doors for wood doors. Because the data in Bergman et al. for the emissions generated by vinyl flooring production came from a 1995 Dutch study, they were not considered relevant for the current analysis, and data from a 2014 Environmental Product Declaration for luxury vinyl tile from Armstrong Flooring were used instead (Armstrong Flooring, 2014).

Based on Smith at al. (2006), the patch cuts would be expected to generate products (excluding wood pulp and fuel wood) containing 34.4 MTCO2e/acre. Though Smith, et al. provide an estimate of the product mix that would be generated from harvesting an 85-year-old oak-pine stand in the Northeast, specific substitution factors were not available for many of the products in the mix. As a result, we applied the emission estimates from Bergman et al. (2013) for the selected hardwood and softwood product classes to all of the hardwood and softwood products (respectively) expected to be produced from this harvest, excluding wood pulp and fuel.

For the patch cuts, with the assumption that all of the hardwood products generated were hardwood lumber and all of the softwood products were softwood lumber, this generated an estimate of 5.0 MTCO2e/acre emitted to produce the wood products (net of emissions from wood burned for energy at the mill, as these emissions are already included in the analysis), compared with 49.9 MTCO2e/acre that would be emitted to produce the alternative non-wood products. This is equivalent to a production-phase substitution factor of approximately 1.3 for the products of this harvest excluding wood pulp and fuel wood.

Applying the same methods and assuming that all softwood products were softwood lumber, this would produce an overall production-phase substitution factor for the harvest of 0.7 if all hardwood harvested exclusive of pulp and energy went to produce flooring and the non-wood alternative (vinyl flooring) would be replaced once during the 30-year timeframe or 1.8 if all hardwood harvested exclusive of pulp and energy went to produce doors. Since a typical harvest produces a mix of end-use products, it is unlikely that either of these extreme values would be achieved, and, based on these methods, the actual production-phase substitution factor achieved is likely to fall in the 1.0 to 1.5 range. We combined this range with the average factor from Leskinen et al. (2018) to generate an estimated range of 0.8 to 1.5 for a production-phase substitution factor for the products of this harvest.

Supplemental Analysis E: Avoided emissions from energy capture

Avoided emissions from generating energy from waste wood products were estimated using estimates of the total emissions with energy capture from Table 6 of Smith et al. (2006) and subtracting the emissions from wood energy used to produce the wood products as estimated in Bergman et al. (2013), which are already accounted for in the production-phase substitution factors. Based on these calculations, approximately 28.1 MT CO2e/acre of the emissions from the products of this harvest through year 30 are associated with energy capture, and thus could displace at least 15.4 MT CO2e/acre of fossil fuel emissions, assuming the alternative fuel is natural gas and using effective emissions factors of 96.6 kg CO2/million BTUs for wood and 53.07 kg CO2/million BTUs for natural gas from the U.S. Energy Information Administration (2016). Using the same methods, 7.2 MT CO2e/acre of the emissions from the products of the light harvest through year 30 are associated with energy capture and could displace at least 4.0 MT CO2e/acre of fossil fuel emissions.

For the hemlock modeling results, emissions from generating energy from waste wood products were estimated using FVS outputs of the total emissions with energy capture through 2051 and subtracting the emissions from wood energy used to produce the wood products, which were calculated using the oak-pine analysis above to estimate the ratio of emissions from wood energy used to produce the wood products to total emissions with energy generation, which was 0.75. As discussed above, the emissions from wood energy used to produce wood products are already accounted for in the production-phase substitution factors. Based on these calculations, approximately 22.8 MT CO2e/acre of the emissions from the products of this harvest through year 30 are associated with energy capture, and thus could displace at least 12.6 MT CO2e/acre of fossil fuel emissions, assuming the alternative fuel is natural gas and using effective emissions factors described above.

Supplemental Analysis F: Landfills

The rate of carbon emitted from landfilled wood products used by Smith, et al. (2006) in their estimates of the fate of carbon in harvested wood products is likely an overestimate, based on more recent evidence. A 2018 review by O'Dwyer et al. found four recent studies estimating emissions from landfilled wood products (using landfill excavation or simulation of landfill conditions), with a *maximum* carbon loss of 23% for softwoods under a laboratory simulation that ran until no more carbon loss could be observed (see Rockett and Giffen 2020 for more detail). Excavation of actual landfilled wood products found less than 2% of carbon was lost over 40 years in a temperate zone landfill, though if this carbon is emitted as methane, it could have greater climate impacts than suggested by the pure carbon balance. Smith et al. (2006) assume that 23% of wood and 56% of paper in landfills is degradable, and that those degradable fractions have a half-life of 14 years. The nondegradable fractions remain in the landfill permanently. Since more recent evidence suggests that the degradable fraction of wood is substantially lower, as indicated by the studies in the O'Dwyer review, the amount of carbon remaining in product plus landfill after 30 years would likely be higher than that shown in Tables 1 and 2.

Supplemental Analysis G: Estimate of wood volume produced under BAU management

To estimate the amount of wood that would be produced within 30 years if an average mixture of BAU silviculture were applied to the average 85-year-old oak-pine stand in this analysis, we began by estimating the volume of wood produced by each type of harvest, as follows.

- Clearcut: All merchantable volume would be removed.
- Regular shelterwood: 30% of merchantable volume is removed in the initial harvest, with an additional 50% removed after 20 years, for a total of 80% of the initial volume removed within 30 years.
- Diameter limit: Based on preliminary results of FVS modeling performed by Spatial Informatics Group for a forthcoming Life Cycle Analysis of cross-laminated timber produced from hemlock grown in Massachusetts, the volume removed in a harvest limited to sawlog quality timber with a 12" minimum dbh would be approximately 71%. This modeling exercise used FIA data from heavily stocked stands (≥8,000 board feet/acre of merchantable sawtimber) with at least 50% of merchantable volume in hemlock. Harvests categorized as "other" types were lumped into this category, as the Massachusetts Bureau of Forestry reporter estimated that these harvests typically remove +/-66% of merchantable volume.
- Salvage: 60% of merchantable volume is removed in the initial harvest, with no further removals within 30 years.
- Small gaps with improvement thinning: Equivalent to Exemplary Forestry silviculture, with 15.8 cords/acre removed.
- Improvement thinning: Equivalent to the thinning component of Exemplary Forestry silviculture, with 10 cords/acre removed.

Next, the harvest volumes per acre were weighted by the share of each type of harvest in the BAU mix, as shown in Table G1, to get an estimate of the average harvested volume per harvested acre under BAU management.

Table G1: Wood produced per acre of heavily stocked stand within 30 years under different silvicultural regimes and under average BAU management

Harvest type	Wood produced	Share of harvests under BAU	Wood produced weighted by share of BAU harvest
	cords/acre	%	cords/acre
Clearcut/seed tree	39	7	2.7
Regular shelterwood	31.2	24	7.5
Diameter limit/other	27.7	4	1.1
Salvage	23.4	13	3.0
Small gaps with improvement thinning	15.8	38	6.0
Improvement thinning alone	10	14	1.4
Total wood produced within 30 years under BAU management			**21.7**

Supplemental Analysis H: Mortality

We expect that thinning could anticipate some fraction of the future mortality expected in the stand. Since the carbon estimates in Smith et al. are based on average stand characteristics for each forest type across the region and are not specific to thinned stands, they do not capture this potential benefit from thinning.

Total mortality in an 85-year-old Eastern white pine/northern red oak/white ash stand over 30 years can be estimated at 7.1 cords/acre, based on the average annual mortality of sound bole volume of trees (at least 5 inches d.b.h./d.r.c.), in cubic feet, on forest land in Massachusetts, Connecticut and Rhode Island from 2019 FIA data (via EVALIDator Version 1.8.0.01), converted to cords using 85 cu. ft./cord.[44] However, the sampling error for this number is quite high—4.9 cords/acre at a 95% confidence level—meaning that the actual mortality could range between 2.2 and 12.0 cords/acre.

Russell et al. (2014) reported decay rates of downed woody debris across the USFS Northeast region. Based on these rates, and assuming that our stand is about half hardwood and half conifer and that the mortality rate is roughly constant over the 30-year period, approximately 50% of the carbon in the trees that die during the analysis period would be emitted by the end of the time period. If we assume that careful thinning could anticipate 50% of mortality, and thus reduce emissions from decomposition by 25% of the carbon contained in the trees otherwise expected to die, this would reduce emissions from the forest by approximately 3.5 MTCO2e/acre over the 30-year period. This can be viewed as a rough estimate of the potential magnitude of the benefit from avoided mortality. However, because of the high uncertainty in the estimated mortality rate, this benefit was not included in the total carbon impacts of Exemplary Forestry silviculture given in Supplemental Analysis A and in the main body of this report.

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[44] Total mortality for the 30-year period was calculated by averaging the annual mortality for 80-100-year-old stands and 100-120-year-old stands, and then multiplying the average annual rate by 30 years.

Appendix

Memo from the Yankee Division of the Society of American Foresters' Working Group on Forest Management and Climate Change

A Perspective on Studies about Forest Disturbance and Forest Carbon

New England forests are diverse and constantly changing. While changes in species mix, age class arrangement, and density at some locations are caused by human activities such as silvicultural treatments and other harvesting, in New England most change in the forest occurs as the result of natural succession and natural disturbances.

Natural succession can be thought of as the somewhat orderly and predictable transition over time from a mix of species that are not tolerant of shade (sun-loving), grow quickly, and are of relatively short life expectancy in the early stages of stand development - to a mix of species that are more tolerant of shade, grow more slowly and live a long time. During the course of natural succession it is possible that several generations of trees will germinate, grow, and die at a particular site. Not all forest types undergo this process in the same way and not all sites support successional transition in the same manner. Understanding the forest type, successional status, and site capabilities (e.g. soils, drainage, slope, bedrock) at any particular location is key to also understanding the growth and change trajectory of a forest stand, or collection of stands in a forested area.

To understand forest carbon sequestration and carbon storage, research studies must acknowledge and take into account the wide diversity of forest sites and conditions that exist, and the inevitable changes that occur in forest ecosystems.

Natural disturbances include storms (wind, rain, snow, ice), drought, insect infestations, disease, fire, and other intense events. Such disturbances occur frequently and influence both forest health and succession. **The following partial listing provides examples of natural disturbance events that have altered forest conditions in Connecticut during the last century**.

- Chestnut blight struck in 1910. At the time Connecticut had about 130 million chestnut trees (1). Within a dozen years, they were all dead.
- In September 1938, a hurricane toppled one-fifth of the large trees in the state. Most of Connecticut's trees were less than 50 years old at the time and native hardwoods under age 40 suffered little damage. Historical records suggest that hurricanes of similar magnitude had struck Connecticut in 1635 and 1815 (2).
- **A parade of insects and diseases, and another hurricane and other windstorms have killed many millions of trees in the second half of the twentieth century and early twenty-first century:**
  1950s: Dutch Elm Disease killed nearly all American elms on city streets and throughout the forest.
  1960s: Gypsy moth and elm spanworm, combined with drought, killed many oaks across the state (3).
  1970s: Red pine scale began its virtually elimination of red pine (4).
  1980s: Another gypsy moth outbreak killed many hemlocks as well as oaks. South Central CT Regional Water Authority (SCCRWA) estimated losing 21,000 large (over 10 inches in diameter) trees from its 18,000 acres of forest (5).
  1985: Hurricane Gloria blew down or heavily damaged large trees on 1/3 of Connecticut's forests, several state parks were closed and many trails were blocked (5). SCCRWA lost another 20,000 large trees (6). Hemlock woolly adelgid began spreading across the state, destroying hemlock groves (7).
  2011 and 2012: Severe storms (Hurricane Irene, Super Storm Sandy, the October Snowstorm Albert) toppled or heavily damaged hundreds of thousands of trees across the state.
  2012: Emerald ash borer (EAB) was found in Connecticut. White ash trees infested by EAB were quickly killed and this process is continuing across CT. White ash accounted for nearly 5% of the carbon in Connecticut trees (8).

2015: Southern pine beetle was confirmed in Connecticut, threatening pitch pine and stressed white pine (9).
2017: Drought and gypsy moth again caused extensive mortality to mature oaks in eastern Connecticut. Some forests lost 20-50% of their trees (10) and on occasion the mortality rate was even higher.
2020: Storm Isaias resulted in damage and loss of hundreds of thousands of trees from wind-throw statewide.

This partial listing serves to illustrate intense and sudden changes that can occur and influence forest species mix, age structure and overall health. New England forests can and do recover from such events, regenerating young forests in many cases. **However, examinations of the role of forests with respect to the sequestration and storage of carbon that assume continuous forest conditions over a long span of time (beyond 20 years) must be questioned with respect to the given regularity of natural disturbances and the projected increase in the frequency and severity of storm events.**

Silvicultural treatments and forest harvesting are disturbances that are human-caused. While such activities do result in changes to forest species mix and structure, these activities also generally result in the utilization of a portion of stored carbon in the form of durable wood products that can continue to store carbon for long periods. Some carbon in harvested trees returns to the soil or the atmosphere. Atmospheric carbon increases are avoided when items and structures are constructed of wood rather than carbon-heavy alternatives such as concrete, steel and plastic.**Thus when comparing forest disturbances with respect to carbon accounting, it is necessary to recognize the portion of carbon stored long-term in durable wood products that result from human-caused disturbances.**

Silviculture is the art and science of sustainably tending forests and woodlands to meet the diverse needs and values of landowners and society

Not all forest harvesting is the same. The science of silviculture applies ecological principles (i.e. what we know about tree species and their abilities to respond to disturbance) in the management of forests. Silvicultural treatments are designed to promote forest health, productivity, wood quality, desirable regeneration, or any number of other goals in various combinations. Not all forest harvesting is part of a silvicultural system or adheres to silvicultural principles. **But where harvests are part of an appropriate silvicultural system, forest health, resiliency, carbon sequestration and storage, habitat quality and recreational goals can all be addressed. Practicing science-based forest management, grounded in proven silvicultural practice when planning forest harvests can enhance forest resilience and forest carbon sequestration and storage region-wide.**

Research studies of forest carbon, broadly projected across the region, that treat all harvesting equally and as simply extractive, fail to acknowledge the role silviculture can have in forest management and the strong potential for active management to: enhance forest resiliency in the face of natural disturbance, complement natural successional trends over time, and increase carbon storage and sequestration in optimal balance with other forest benefits.

Bottomline: In order to accurately assess and predict what is happening with regard to forest carbon sequestration and storage in Connecticut's forests, future research and modeling studies **must** take into account:

- the wide diversity of forest types, sites and conditions which exist,
- the role of natural succession and natural disturbances which occur on a regular basis,
- the role of silviculture in active forest management,
- the fact that continual change occurs in forest ecosystems and that continuous forest conditions cannot be assumed over a long span of time (beyond 20 years), and
- the portion of carbon that is stored long-term in durable wood products resulting from human-caused uses.

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