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Storing More Carbon by Improving Forest Management in the Acadian Forest of New England, USA

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Abstract: The capacity of forests to store carbon, combined with time-tested approaches to managing forests, make forests a useful tool for atmospheric carbon mitigation. The primary goals of this study are to determine the amount of unrealized mitigation available from Improved Forest Management (IFM) in the Acadian Forest of New England in the northeastern U.S., and to demonstrate how this mitigation can feasibly be attained. This study used the Forest Vegetation Simulator (FVS) to model the impacts of IFM practices articulated by the New England Forestry Foundation on carbon storage in the Acadian Forest. Our results, together with empirical data from well-managed forests, show that if the modeled improved management is employed on privately owned timberland across the Acadian Forest of New England, carbon storage could be increased by 488 Tg CO_2e. Our financial modeling shows that IFM could be funded in this region by combining income from carbon markets with the philanthropic funding of conservation easements, timber revenues, and capital investments from private investors who prioritize social and economic goals alongside financial returns. This study adds to the body of evidence from around the world that the potential for managed forests to contribute to climate change mitigation has not been fully realized.

Keywords: carbon storage; forest management; mitigating climate change; natural climate solutions; improved forest management

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1. Introduction

The world's forests play a key role in mitigating climate change by both storing and sequestering carbon. Global forest ecosystems are estimated to store 861 Pg C, with 363 Pg C in live biomass (above and below ground; [1]). In addition, managed forests produce durable wood products that can store carbon and reduce greenhouse gas (GHG) emissions when they are substituted for alternative products with higher embodied emissions [2].

Forests already serve as a carbon sink globally, but recent work has demonstrated their capacity to do far more to mitigate climate change, and carbon markets are rapidly developing to incentivize a shift in management [3–5]. In contrast with other carbon sinks, such as blue carbon or peatlands, resource managers have more than a century of experience managing forests for a variety of outcomes, which can now include carbon storage [6,7]. Improved Forest Management (IFM) can lead to substantially increased carbon storage simultaneous with increased timber harvests, which allow for additional carbon storage in harvested wood products and reduced GHG emissions from substituting wood for more CO_2-emission-intensive materials [8]. This increase in carbon storage also produces a commodity product in terms of marketable carbon credits where markets exist, an increasingly common situation. While the specific opportunity will vary by forest type and region, studies indicate strong potential for increased climate mitigation in northeastern North America resulting from IFM in this region [9–11]. Additional analyses are needed to help document the scope and scale of such opportunities more broadly [7,12]. In this study, we assess the potential impacts on global GHG levels from IFM in the Acadian Forest of New England (see Figure 1).

We recognize that modern, climate-smart forest management must consider both the role forests play in mitigating global climate change and the need to promote the adaptation of forests to climate change by improving forest resistance, resilience, and response to future climate conditions [6,13]. IFM can benefit both mitigation and adaptation, but the primary focus of this paper is on mitigation.

We also recognize that forests can mitigate climate change in several different ways beyond storing carbon—for example, by changing the albedo of the Earth's surface and producing biogenic volatile organic compounds (BVOCs), which influence the reflectivity of the Earth's atmosphere [14–16]. In fact, in some regions and circumstances, forests may have a greater influence on climate via these other pathways than through carbon sequestration [16–19]. Though all the ways forests can influence climate need to be considered in evaluating the climate impacts of forest management, many of these influences are not well understood for New England forests (or for forests more generally), and quantifying their effects is beyond the scope of this article. Instead, we address carbon storage specifically.

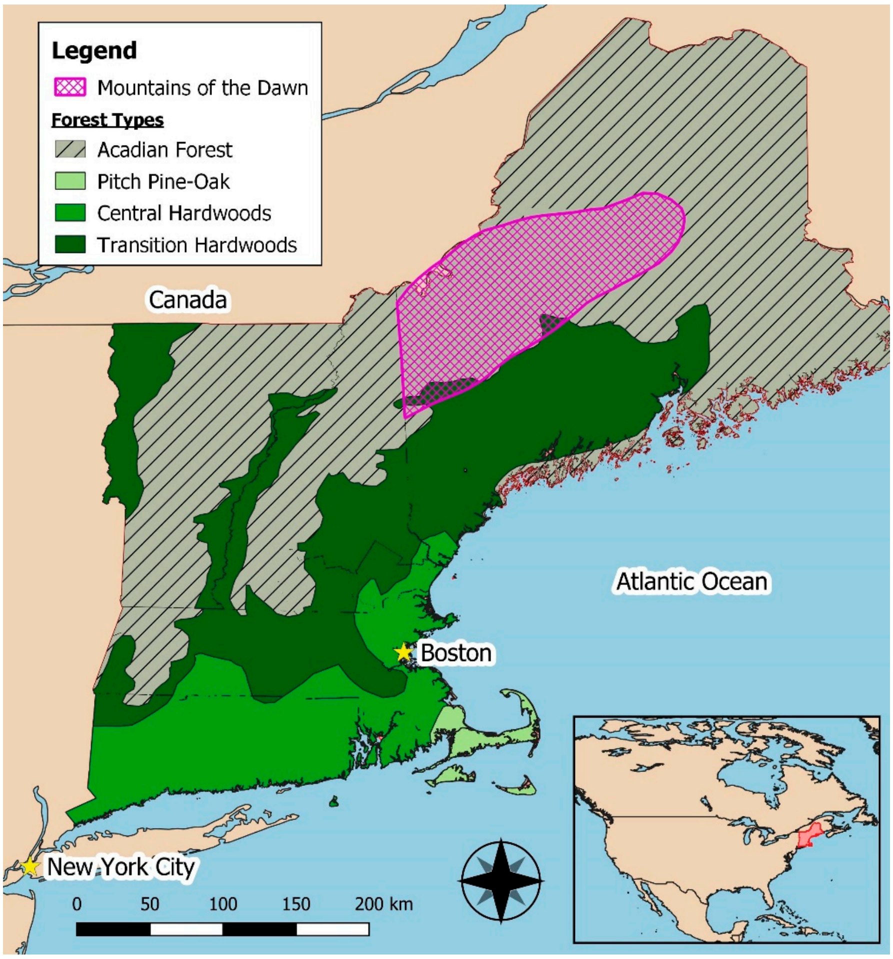

Figure 1. Forest regions of New England and mountains of the Dawn region. New England includes the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut. Forest regions adapted from Foster [20].

Forests have the potential to help mitigate climate change via a wide array of pathways and management strategies, commonly referred to as Natural Climate Solutions (NCS) [5,21,22]. While NCS strategies all have value, we focus exclusively on IFM in this work. Given that most of New England is already forested, and the forests of New England largely regenerate naturally, other NCS pathways commonly recommended for increasing forest carbon, such as planting more forest trees, do not offer as much potential in this region as IFM. Thus, our analysis evaluates the opportunity for increasing carbon storage on private timberland in the Acadian Region in northern New England through IFM that addresses carbon together with other important forest values, including wildlife habitat.

1.1. The Acadian Forest

The Acadian Forest lies in the transition zone between the temperate deciduous forest and the boreal forest of eastern North America [23]. We defined the Acadian Forest region as the zone mapped as Northern Hardwoods and Spruce–Fir by Foster [20], based on Westveld et al. [24]. The Acadian Forest occupies approximately 9.8 million hectares (24 million acres) in New England and covers the eastern and northern portions of the state of Maine, as well as the mountains of Maine and the White and Green Mountain ranges in the states of New Hampshire and Vermont. The Acadian Forest is surrounded by the Transition Hardwoods zone, with Central Hardwoods and Pitch Pine–Oak zones occurring to the south [20] (Figure 1). The Acadian Forest region is one of the largest areas of intact forest in the eastern U.S., and it provides many ecological services, including protecting the quality of large flows of water, serving as the basis for numerous recreational experiences and industries, and providing habitats for a wide range of native wildlife species, including rare species of both animals and plants.

Acadian forest types, as defined in Supplementary Materials SA, include northern hardwoods, dominated by beech (*Fagus grandifolia* Ehrh.), birch (*Betula alleghenienses* Britton, *Betula papyrifera* Marshall), and maple (*Acer saccharum* Marshall, *Acer rubrum* L.), which occupies approximately 31% of the region modeled; spruce–fir, dominated by red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.), which occupies approximately 35% of the area; and mixed wood (a mix of all these species), covering approximately 34% of the region. Scattered but coherent stands of white pine (*Pinus strobus* L.) and bottomland hardwoods also occur, but occupy less of the landscape.

Maine is the major timber-producing state in the New England region and contains most of the Acadian Forest of New England. Maine's forests have been harvested commercially since at least the mid-19th century [25,26]. Over the last 10 years, Maine forests have produced approximately 12.6 Tg (approximately 13.2 million m^3 or 5.5 million cords) of green wood per year, of which approximately 53% was softwood and 47% hardwood [27]. Unlike in the western U.S., the majority of the timberland in this region is privately owned; 92% of Maine and 78% of the Acadian Forest region is privately owned [28].

The results presented in this paper are largely based on analyses conducted on a 1.7-million-hectare region of the Acadian Forest in northwestern Maine known as the Mountains of the Dawn (MotD; see Figure 1), which shares the same forest types, species, and management approaches as the rest of the Acadian Forest in New England.

1.2. Current Conditions in the Acadian Forest

The average standing volume on timberland in the Acadian Forest of New England is, at present, approximately 140 m^3 ha^{-1} (23.5 cords per acre) (sound merchantable volume of live trees with a 12.7 cm diameter at breast height (dbh; 1.37 m) and taller [28]).

The average standing volume per hectare of private forest land varies widely by county across New England (Figure 2), with stocking lowest in portions of Maine, where recent harvest rates have been higher than in other parts of New England [29–31].

A review of recent data from the U.S. Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis (FIA) program for plots in Maine (Figure 3) shows that stand growth rates are higher in areas with higher timber volume, suggesting that annual growth, and thus timber harvests, could be increased if stocking was increased.

The adequacy of stocking at present becomes a serious concern in the context of current trends in species composition and tree form. In recent decades, climate change and traditional forest management approaches have led to shifts in the species composition of the Acadian Forest, a process predicted to impact many forested landscapes across the globe [32,33]. The Acadian Forest in particular is already seeing the northern hardwood type undergo a shift toward more beech-dominated stands [29,34]. This presents concerns for forest management, as beech is a less desirable timber species compared with other hardwood species, largely due to a widespread disease and poor form, and tends to limit regeneration of other species [34]. Balsam fir, which is highly susceptible to periodic outbreaks of eastern spruce budworm (*Choristoneura fumiferana* Clemens), is also increasing in northern New England [35]. Gunn et al. [35] estimated that 40% of the forestland in northern New England (Maine, New Hampshire, and Vermont) is in a "degraded" condition, defined as stands that do not contain sufficient density of trees classified as acceptable growing stock of species of primary or secondary commercial value to be able to fully occupy the growing space of the site within 10 years. Furthermore, evidence shows that harvesting trends at present are pushing stands in the Acadian Forest toward marginal commercial species, such as beech and red maple [29,34]. These trends imply a future in which the Acadian Forest is increasingly dominated by species with substantial disease and pest pressure and marginal commercial value [29,35]. In the absence of IFM, these trends are likely to make the Acadian Forest less resilient to future climate change and reduce its climate mitigation potential.

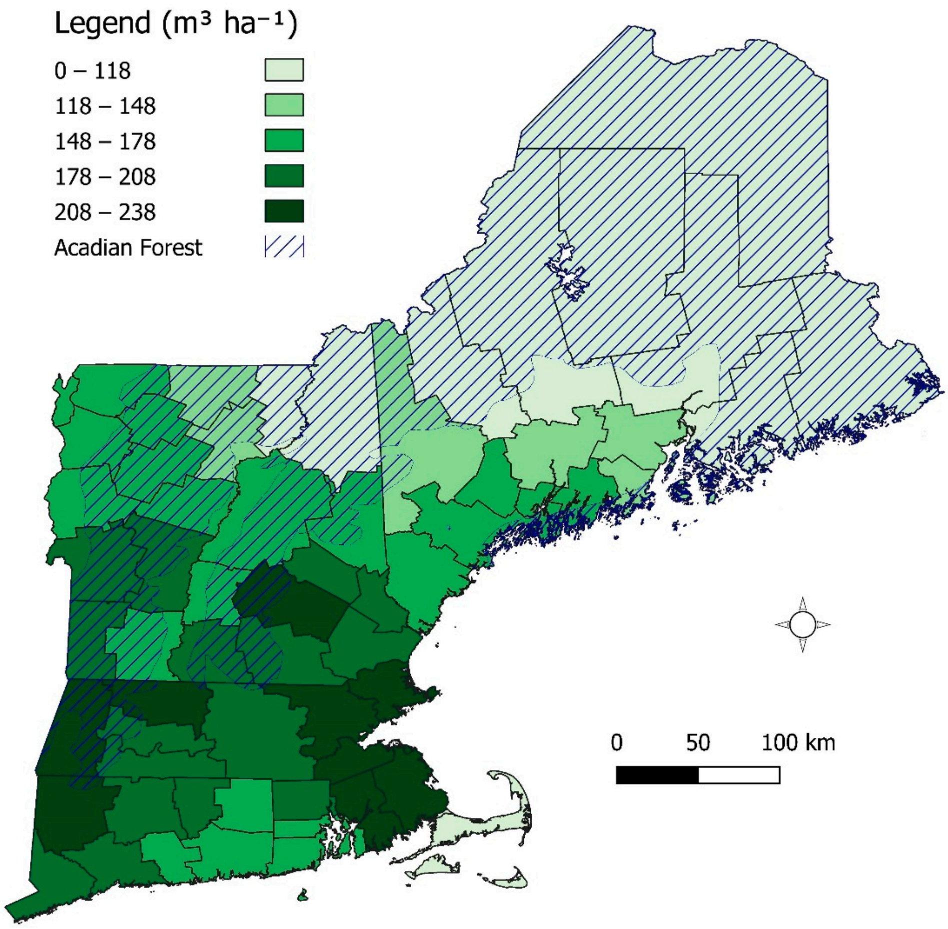

Figure 2. Stocking of merchantable timber on private forest land in New England, by county. Counties are shaded based on net merchantable bole volume of live trees (at least 12.7 cm diameter at breast height) per hectare of private forest land, averaged by county or county group. County groups were used for some small counties to avoid anomalies from very low sample sizes in the Forest Inventory and Analysis program data. Overlay of Acadian Forest is based on Northern Hardwoods and Spruce–Fir region from Foster [20].

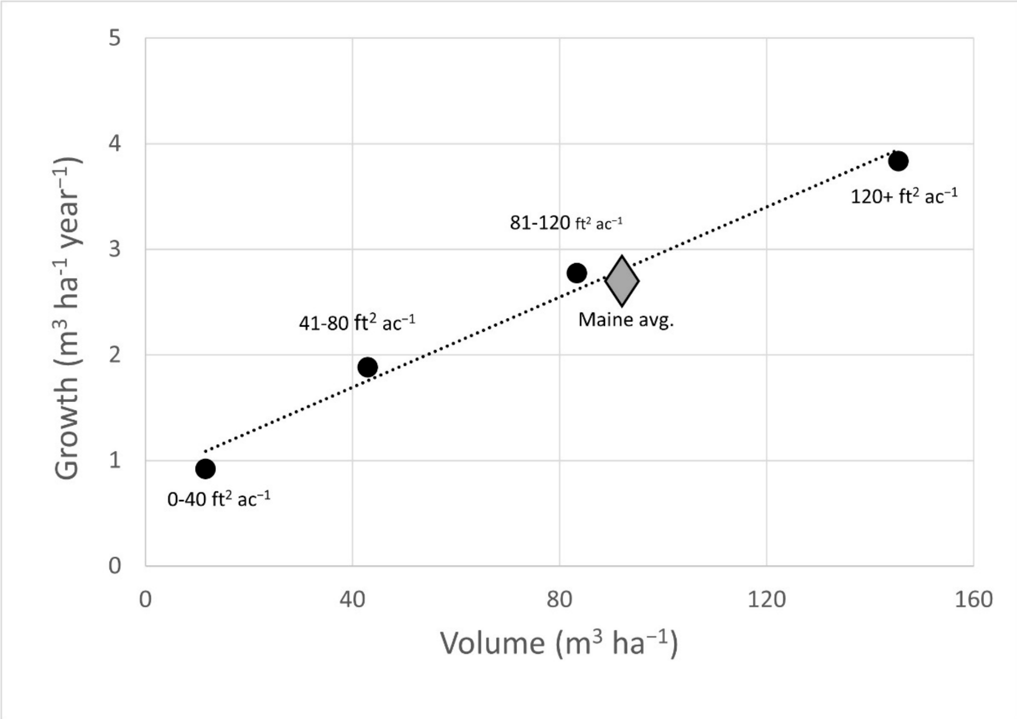

Figure 3. Growth as a function of volume of growing stock for Maine forests. Round dots represent mean growth versus mean volume summarized by basal area stocking class, based on queries of 2019 Forest Inventory and Analysis (FIA) program data for Maine using the U.S. Department of Agriculture Forest Service Evalidator program. (Basal area stocking classes are defined by FIA in ft^2 ac^{-1}, as shown.) The gray diamond represents the statewide average for Maine (including all forest types). Growth is average annual net growth of merchantable bole volume of growing-stock trees at least 12.7 cm dbh (diameter at breast height) on timberland; volume is net merchantable bole volume of growing-stock trees at least 12.7 cm dbh on timberland. Refined from Seymour (pers. comm.).

At present, the conditions in the Acadian Forest also do not provide an optimal mix of habitat for native wildlife species. An analysis of wildlife habitats in the Mountains of the Dawn [36] identified a number of strengths, such as a relatively light human footprint and good landscape connectivity compared with other temperate mixed wood forests, but also important gaps in habitat conditions based on standards developed by wildlife ecologists [37]. For example, forests in the region contain few old and very old trees and late-successional communities, which are required by a wide array of wildlife species, and harvest practices at present do not provide sufficient high-quality, early successional habitats needed by other species [36].

The stand size class distribution at present in the MotD study area differs substantially from the distribution recommended by DeGraaf et al. [37] to optimize habitat values for native wildlife on lands being actively managed for timber production (Figure S16). Altered forest management regimes that create increased late successional habitat features would move the landscape toward this recommended distribution.

1.3. Exemplary Forestry Standards

The New England Forestry Foundation (NEFF) has developed forest management standards (Exemplary Forestry™, or EF), which include a focus on mitigating climate change, alongside other goals—e.g., improving wildlife habitat [38]. The standards call for forestry that contributes to climate mitigation by increasing forest stocking and producing more timber, as both can reduce greenhouse gas levels (for information on the benefits of substituting wood for other materials, see [3,39–42]). Under EF, forests are managed to increase resistance to climate change and resilience and to adapt to future climatic conditions. Other silvicultural systems can produce similar or even greater gains for carbon sequestration [9,11,43], but will not have the same emphasis on protecting other environmental values (e.g., enhancing wildlife habitat).

These standards were developed in consultation with some of the region's leading ecologists, wildlife biologists, and silviculturists. The silviculture to be used to achieve the results called for in the EF standards, in general, includes small-gap irregular shelterwood (also known as small-group shelterwood), with thinning from below between the small gaps, as well as conventional (regular) shelterwood to produce larger patches of early successional/young forest habitat. Crop trees are managed on +/−100-year rotations. This silviculture was designed to meet the habitat needs of two umbrella wildlife species, the American marten (*Martes americana* (Turton, 1806)) and Canada lynx (*Lynx canadensis* Kerr 1792), whose required habitats would also meet the habitat needs of more than 85% of the vertebrate forest-dwelling wildlife species in the region [44].

Forests that are managed to meet the EF standards will approach the stand size-class distribution recommended by DeGraaf et al. [37] as optimal for native wildlife, and will exhibit stocking that, on average, fully occupies the site. This is defined as target stocking at or above the B line, based on regional stand stocking guides for hardwoods [45] and spruce–fir [46] (see Figure 4 for a sample stocking guide and Supplementary Materials SA for a detailed description of how the regional stocking guides were used to develop silvicultural prescriptions). In the Acadian Forest, this will, on average, result in standing volumes of at least 149 m^3 ha^{-1} (25 cords per acre).

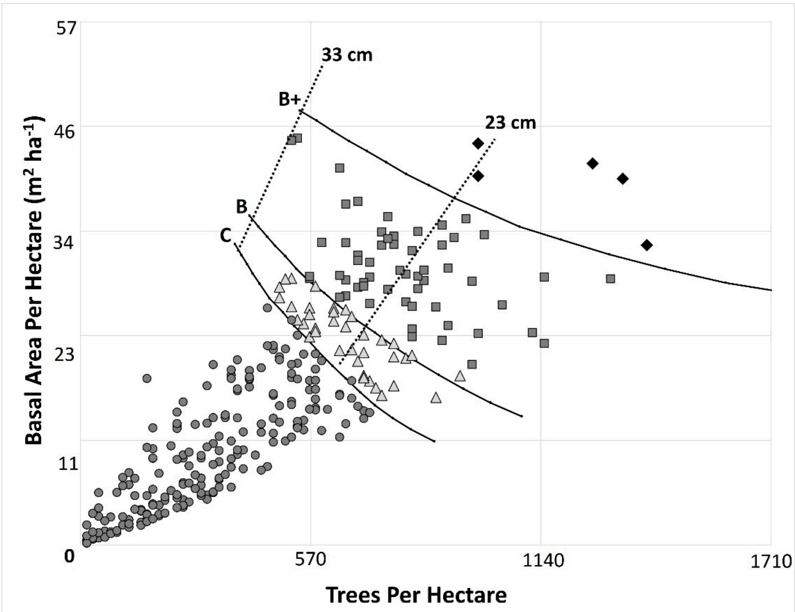

Figure 4. Example of a spruce–fir stocking guide, populated with the Forest Inventory and Analysis plots from this study. Diamonds indicate plots that have stocking at the B+ line or above. Squares are <B+ line but >B line. Triangles are plots with stocking between the B and C lines, and circles are plots with stocking below the C line. Dotted lines indicate quadratic mean diameter at breast height of 23 cm (minimum sawtimber size for spruce–fir in this region) and 33 cm.

1.4. Study Goals

The primary goals of this study were to determine the amount of unrealized mitigation available from IFM in the Acadian Forest ecosystem and demonstrate how this mitigation can feasibly be attained. We assessed the potential for IFM to increase the stocking (standing timber volume and carbon storage) of northern New England forests. Beyond increased carbon storage in the forest, increased stocking would have a number of additional benefits, including an increased quantity and quality of timber produced, economic incentives for maintaining forests as forests, and additional climate change mitigation from substituting long-lived wood products for more carbon-intensive materials [3,39–42]. This type of management can also benefit wildlife habitat and maintain other forest values, such as water quality protection. We also assessed the financial feasibility of implementing IFM for private landowners.

2. Materials and Methods

2.1. Growth and Yield Modeling

We modeled the implementation of the Acadian Forest EF standards compared with management to maximize the Net Present Value (NPV) in the Mountains of the Dawn region of northwestern Maine (Figure 1, above). The modeling methods are summarized here; detailed methods are included in Supplementary Materials SA. The modeled forest was characterized using FIA plot data from 2017, which were sorted into 46 "cases," with each case consisting of a forest type (i.e., northern hardwoods, spruce–fir, or mixed wood), a stand size class (i.e., saplings, poletimber, or sawtimber), and a stocking level (A, B, or C line according to regional stand stocking guides [45,46]). See Table S5 for more information on the 46 cases defined and the share of the total study area represented by each case. Figure 4 shows the stocking of the individual FIA plots in the spruce–fir forest type by comparison to B- and C-line stockings from Frank and Bjorkbom [46]. The B+ line was added as a more practical goal for increased stocking in spruce–fir stands because managed spruce–fir stands rarely reach the A line presented in the original stocking guide. Within a given forest type and stand size class, each plot was assigned to a silvicultural treatment based on where it fell on the stocking guide.

For each case, a detailed silvicultural prescription was developed based on the EF standards. In brief, the prescriptions call for a waiting period of 10–30 years for stands with initial stocking below the A line (B+ line for spruce–fir), to allow the stand to grow in both stem size and site occupancy. Following the waiting period, or immediately for stands with stocking at or above the A/B+ line, the model implemented irregular shelterwood silviculture, defined as harvesting 20% of the stand in small (<2 ha) gaps and thinning the remainder of the stand to remove poorer quality trees and increase the growth of desirable trees. Legacy trees are left in the gaps to provide structure, and gaps are expanded at 20-year intervals, again with thinning between the gaps. For the management to maximize short-term cash flows, harvesting was constrained to comply with state law: any stand with basal area of at least 17.2 m^2 ha^{-1} was thinned from above to a residual basal area of 6.9 m^2 ha^{-1}, with the residual volume removed 10 years later. See Table S6 for the complete set of detailed prescriptions.

The Northeast variant of the U.S. Forest Service Forest Vegetation Simulator (FVS) model [47] was used to model growth and harvest for each of the 46 cases under the silviculture prescribed for EF, as well as a contrasting scenario in which the forest is managed to maximize NPV or, put another way, to maximize short-term cash flows. While most landowners in the region do not manage to maximize NPV, an increase in forest land ownership by financial investors in the region over the past several decades, together with a tendency for these landowners to harvest more heavily than other types of owners, suggests that an increasing number of landowners feel financial pressure to increase short-term cash flows [29,48–50]. Management to maximize NPV thus represents an extreme case, rather than typical management across landowners. However, the maximization of NPV is a standard component of counterfactual analysis in carbon accounting methodologies, such as that used by the California Air Resources Board [51], and we believe this scenario provides a useful comparison to what strictly financial considerations can encourage. The results from the 46 cases modeled were weighted based on the share of the landscape represented by each case to generate results for the study area as a whole.

2.2. Estimating Carbon Impacts of EF

As part of the growth and yield modeling described above and detailed in Supplementary Materials SA, carbon stocking was modeled in FVS using FVS Fuels and Fires Extension. Throughout this study, forest carbon was defined as all carbon pools reported by FVS. Carbon in mineral soil was excluded because the scientific understanding to date does not offer clear empirical data regarding the effects of forest management practices on soil carbon pools [52–54].

In order to estimate how much more carbon could be stored in the Acadian Forest in this region if EF were practiced on private timberland throughout New England with current timber volumes below the ideal levels, we used the FIA data to calculate the mean standing volume and mean forest carbon per hectare on private timberland in the Acadian Forest of New England by county at present. We focused on private timberland, as defined by FIA [28], because average timber volume and average carbon per area are higher on public lands than on private lands in this region (based on 2019 FIA data). Higher carbon in public lands is largely the result of public land policy and administrative restrictions that lead to longer rotations. Thus, the vast majority of the opportunity for increasing carbon storage in the forest occurs on private timberland. Because we do not have reliable information on the management practices at present across the region, we used current conditions as the baseline for calculating the potential increase in carbon storage in the forest.

The mean carbon storage by county at present was compared with the potential carbon stocking that would be expected under EF management, as estimated by the modeling of the MotD region described above. For counties with an average carbon per hectare value lower than the calculated average for lands with target volumes, the deficit, or "carbon gap", was calculated as:

$$C_{Gap} = \left(\widehat{C}_i - \widehat{C_{EF}}\right) * A_i \quad (1)$$

where $\widehat{C}_i$ is the average carbon per hectare on private timberland within the Acadian Forest in county I, $\widehat{C_{EF}}$ is the average carbon per hectare expected under EF management, and A_i is the area of private timberland in the Acadian Forest in county *i*.

The carbon gaps for each county were summed to create an estimate of the total opportunity to increase carbon storage in the forest over the long term in the Acadian Forest of New England.

2.3. Financial Modeling

Financial modeling was conducted to evaluate the economic feasibility of implementing the type of improved silviculture proposed in this study: specifically, whether Exemplary Forestry could provide positive returns for an investor without requiring a commitment of many decades. We modeled a 15-year investment period to reflect the time scale on which many financial investors in timberland, such as Timber Investment Management Organizations, tend to operate, as these investors own a substantial and increasing share of timberland in the region [48,50]. In order to generate a rate of return that could be acceptable to investors, the modeled scenario combined a philanthropically funded conservation easement and the sale of carbon credits, both of which are feasible in the region, with timber revenues from the Exemplary Forestry management modeled in this study.

We calculated discounted cash flows based on the harvests and carbon volumes predicted by the FVS modeling and typical management costs determined by actual and estimated management cost data provided by four forest landowners and two forest management companies in the region. Timber pricing was based on an average of eight available sources of stumpage prices for northern New England (Supplementary Materials SB). The model assumed a price for U.S. IFM carbon offsets starting at USD 9.50 per tonne and increasing by 6% per year. The starting price is based on the reference price used by the American Carbon Registry [55], though actual carbon prices are highly variable. Recently developed carbon projects have had widely divergent prices per tonne, including "premiums" paid for high quality credits, such as those that might result from EF standards. Thus, we considered USD 9.50/tonne a conservative starting price. The financial model is sensitive to assumptions about carbon prices, which are difficult to predict. Prices in the voluntary carbon markets have been volatile, but forestry and land use credits, and particularly those that remove carbon from the atmosphere, such as IFM, have consistently fetched higher than average prices.

Conservation easement pricing was based on a third-party evaluation of the EF standards and an estimation of the impact of EF on the fair market value of timberland in similar parts of Maine. The value of a typical working forest easement in western Maine was estimated based on a review of sales of Maine timberland parcels 800–20,000 ha in size that occurred between 2010 and 2019. Twenty-two sales of timberland encumbered by working forest conservation easements and thirty-nine sales of unencumbered timberland were included, with sales of parcels in western Maine given more weight. Because an easement requiring improved silviculture would be more restrictive than the typical working forest easement in place at present in Maine, the appraiser used a discounted cash flow analysis to compare the expected value of a typical easement-encumbered western Maine property with the expected value of a property encumbered with an Exemplary Forestry type of easement. For the appraisal process, the EF standards were simplified to a requirement that a minimum stocking level of 119 m^3 ha^{-1} must be reached before significant commercial timber harvests can be undertaken.

Two independent experts (Jack Lutz of Forest Research Group and Hunter Hopcroft of Quantified Ventures) contributed to the development and review of the financial model. See Supplementary Materials SC and SD for the complete model.

3. Results

Implementing EF management across the Mountains of the Dawn study area results in increasing volume in the forest, as well as improving the quality of both residual trees and the wood harvested over the 60 years modeled (Figure 5 and Figure S3). In contrast, managing to maximize NPV results, over time, in lower standing volumes, especially of sawtimber, and harvests of smaller, lower-value trees. The total harvest over the 60-year period modeled was 65 m^3 ha^{-1} of sawtimber and 120 m^3 ha^{-1} of pulpwood under EF management, compared with 37 m^3 ha^{-1} of sawtimber and 246 m^3 ha^{-1} of pulpwood under management to maximize NPV. After 60 years, the residual stocking under EF management was 155 m^3 ha^{-1}, including 56 m^3 ha^{-1} of sawtimber, compared with 19 m^3 ha^{-1} (with negligible sawtimber) remaining in the forest following 60 years of management to maximize NPV.

3.1. Carbon Storage in the Forest

By comparison to the initial condition, implementing EF increases carbon stocking in the forest (all pools except mineral soil) by 78 Mg ha^{-1} CO_2e within 25 years (see Figure 6). Perhaps most importantly, EF management maintains this higher carbon storage (an average of 413 Mg ha^{-1} CO_2e) in the forest over the modeled time period. In contrast, management to maximize NPV does not achieve the same results: while carbon stocking does increase for a period of time, it then declines substantially.

As shown in Figure 2, the Acadian Forest portions of 15 New England counties have average timber volumes below what is expected under EF management (148 m^3 ha^{-1}). These counties represent an opportunity to increase carbon storage in the forest by implementing EF management to achieve higher volumes and higher carbon storage compared with conditions at present (Figure 7 and Table A1). If the EF standards were implemented across the Acadian Forest of New England, such that private timberland in the Acadian Forest region in each New England county reached the modeled minimum average of 413 Mg ha^{-1} CO_2e, an additional 488 Tg of carbon would be stored in the forest across the region. This represents a 26% increase above storage at present on private lands in understocked counties.

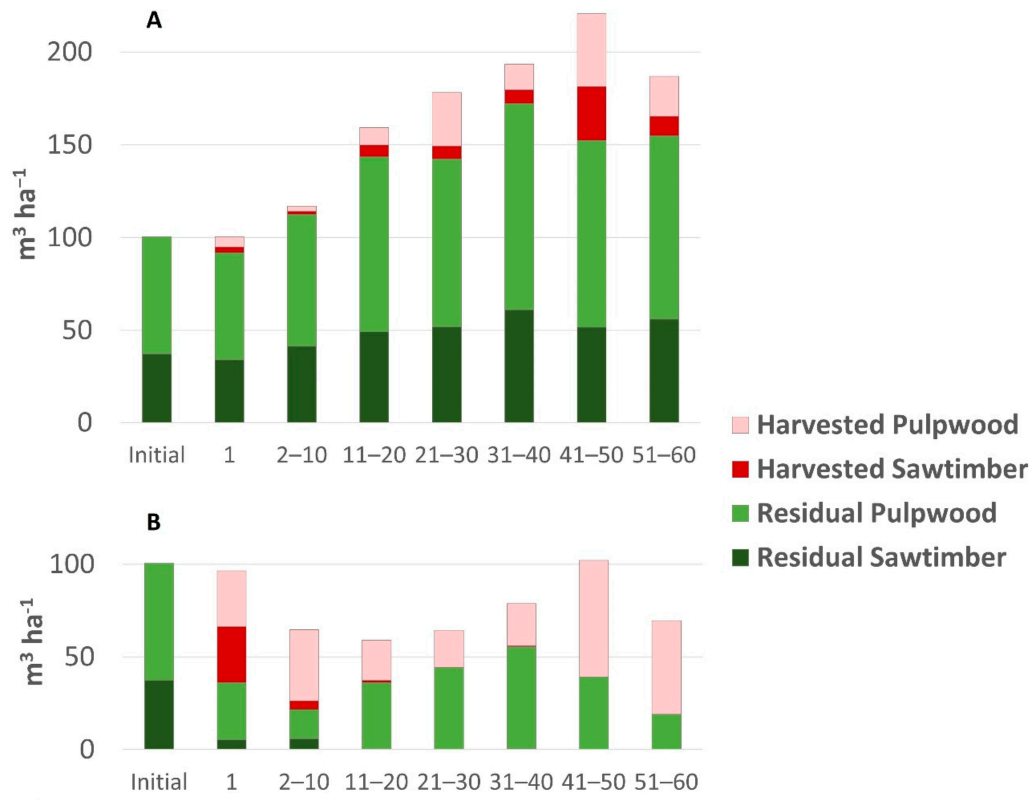

Figure 5. Modeling results from two management regimes in the Mountains of the Dawn region: (**A**) decadal yield and residual stocking from EF management, and (**B**) management to maximize net present value; residual stocking is merchantable volume remaining in the forest at the end of each time period shown. See Supplementary Materials SA for more details.

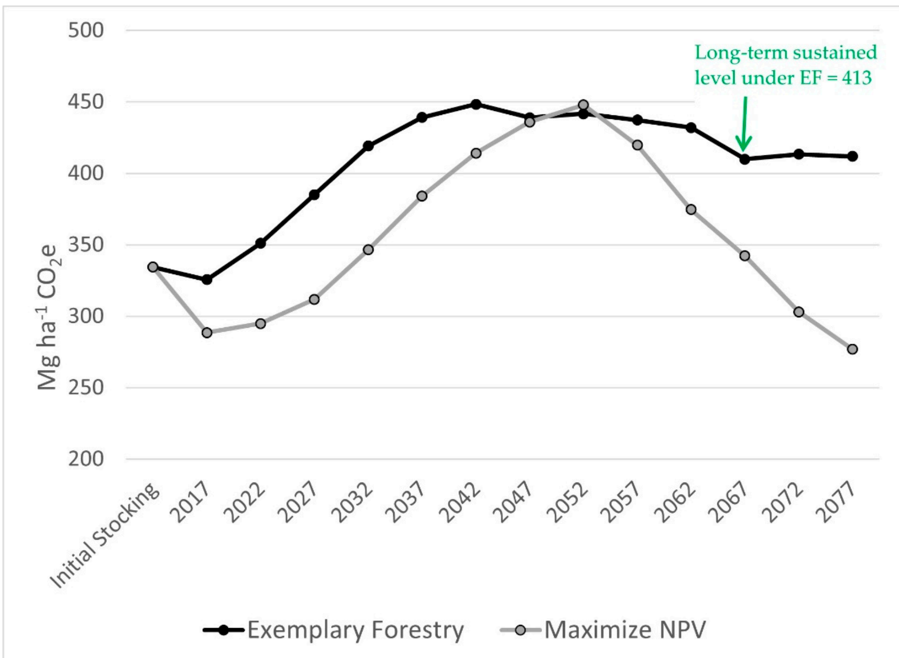

Figure 6. In-forest carbon storage from practicing Exemplary Forestry vs. maximizing short-term cash flows (or net present value) over 60 years in a forest representative of the Mountains of the Dawn region. See Figure S5 for more detailed results.

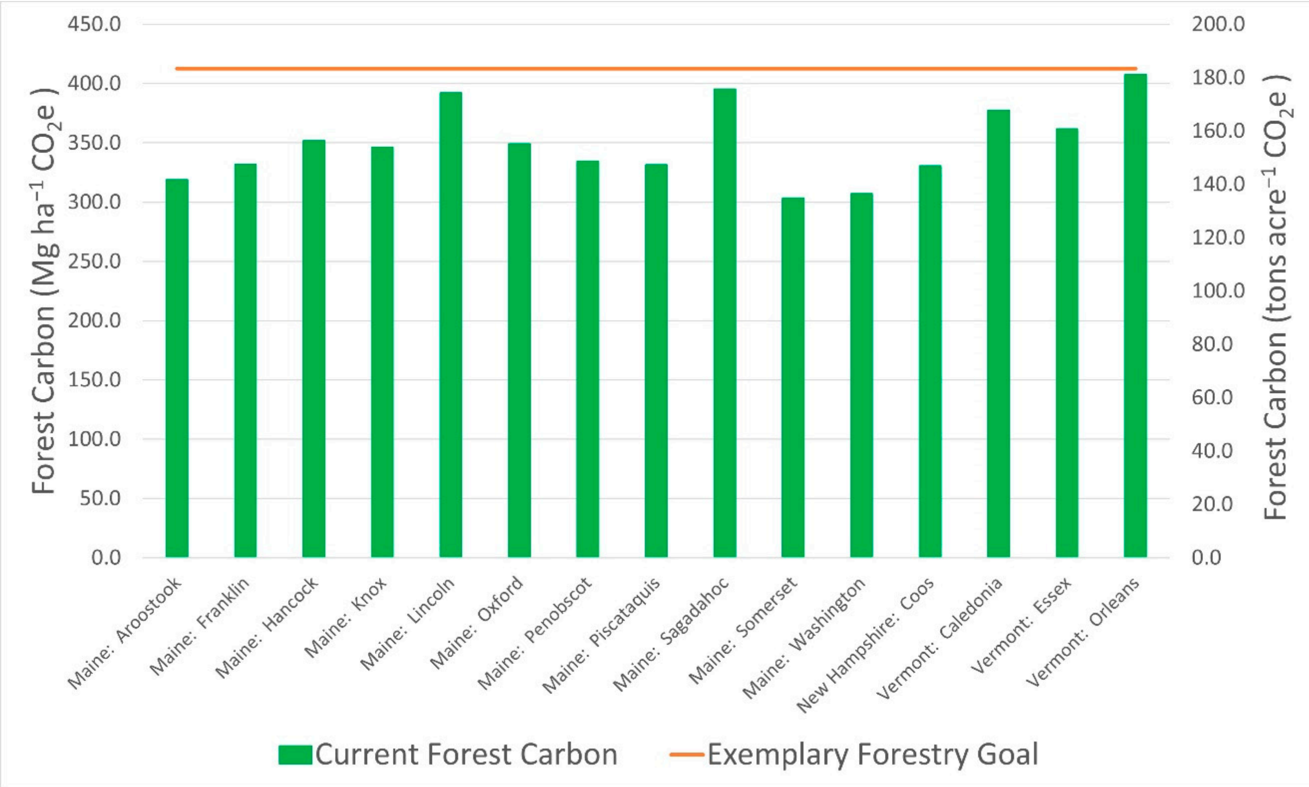

Figure 7. Carbon storage per hectare on privately owned timberland in the Acadian Forest of New England in counties with average carbon storage below 413 Mg ha^{-1} CO_2e. The gap between carbon storage at present (green bars) and the expected storage under EF management (orange line) is the average carbon storage opportunity per hectare.

3.2. Financial Modeling

Using conservative assumptions, the results of the financial modeling indicate that if EF management is combined with the sale of carbon and conservation easements typical of conservation projects in the region, real returns would be in the vicinity of 4.4% over a 15-year period, depending on the market value of carbon and the price per unit area of the conservation easement, as well as the valuation of the land after 15 years. Table 1 provides a summary of the projected revenues and costs for a 2000 ha parcel in average condition representative of northwestern Maine. For comparison, managing the same parcel to maximize NPV is predicted to yield a real return of approximately 5.7%, based on the sum of the discounted cash flow for all of the timber proceeds for the life of the property. Thus, the combined income from the sale of carbon credits and a conservation easement, combined with timber revenues, can generate returns that approach but do not equal the maximum potential returns from timberland investments.

Table 1. Costs, revenues, and internal rate of return (IRR) for a parcel in average condition for the modeled region of northwestern Maine under EF management, assuming a 15-year holding period.

Summary		
Acquisition		
	Total hectares	2000
	Price per hectare	USD 2471
	- Plus: transactions costs	USD 111
	Total acquisition price per hectare	USD 2582

Table 1. *Cont.*

Summary		
Capital stack		
	All in acquisition cost	USD 5,164,495
	Total equity required (35%)	USD 1,806,701
	Philanthropic easement (48%)	USD 2,471,050
	Debt/loan (17%)	USD 886,744
Return to equity (real)		
	Investor hold period (years)	15
	- Whole dollar profit	USD 3,240,994
	- Multiple on invested capital	2.97
	Holding period nominal IRR	7.09%
	Holding period real IRR	4.43%
Revenues Over Holding Period		
Carbon		
	Average carbon credits per hectare per year for holding period	5.79
	Price per credit in year 1 (USD/Mg CO_2e))	USD 6.00
	Growth rate of carbon pricing (per year)	3%
	Weighted average carbon price over 15 years (holding period)	USD 10.92
	Total carbon revenue (per hectare)	USD 949
	Total carbon revenue	USD 1,898,549
Timber		
	Total timber revenue (per hectare)	USD 202
	Total timber revenue	USD 404,628
Conservation easement		
	Easement value (% of acquisition cost)	50%
	Easement value (per hectare)	USD 1236
	Total easement value	USD 2,471,050
Recreation		
	Recreation revenue (per hectare, year 1) (existing camp leases)	USD 0.72
	Growth in recreation revenue (per year)	2%
	Total recreation revenue (per hectare)	USD 12.45
	Total recreation value	USD 24,907
Disposition		
	Post easement (encumbered) value (per hectare)	USD 6277
	Additional discount for Exemplary Forestry easement	10%
	Growth rate in value	6%
	- Less: EFM discount (60%)	USD (3776)
	Encumbered value at disposition (per hectare)	USD 2511
	Disposition value	USD 4,971,650
Expenses		
	Total expenses (per hectare)	USD (338)
	Total expenses value	USD (675,072)

Returns will of course vary from parcel to parcel depending on purchase price, stocking, markets for carbon easements, and other factors. In general, the larger the parcel, the lower the price per unit area. Larger parcels are also more likely to resemble the average forest condition and, thus, to create yields similar to the forest modeled here, which is intended to be representative of the whole region.

4. Discussion

4.1. Regional GHG Emissions Context

Our analysis of how the improved management of New England's forests could enhance carbon storage is illustrative of the opportunities that exist to use forests to reduce atmospheric GHG levels in landscapes where forest carbon stocks have been reduced, whether due to harvesting, fire, insects, disease, or other causes. It shows that, even while protecting other values, the opportunity to increase carbon storage in the Acadian Forest of New England by increasing timber stocking is substantial, equivalent to taking a million cars off the road for over a century based on [56]. To put this in the context of climate goals, the New England region produces approximately 145 Mt of CO_2e in energy-related emissions per year as of 2019 [57]. For New England to reach net-zero emissions by 2050 would require net reductions of 2136 Mt CO_2e (assuming a constant annual reduction of 4.67 Mt from emissions to date). Thus, implementing EF management on private timberlands throughout the Acadian Forest of New England could address approximately 23% of the emission reductions needed for New England to reach a net-zero level by 2050.

Several recent studies have assessed carbon sequestration or storage potential for this region. Meyer et al. [58] estimated the potential to increase carbon storage on understocked timberland across all forest types in New England and found that forest management that increases stocking on lands with low to moderate stocking could increase carbon storage in New England forests by 203 Tg CO_2e over 30 years if implemented on half of inadequately stocked lands. This implies a total potential for increased storage of 406 Tg CO_2e if implemented on all inadequately stocked lands (our interpretation). Though Meyer et al. used different methods to estimate the additional storage potential from IFM, their results, similar to ours, suggest that the opportunity is great.

Based on recent harvest rates from FIA plot data, Brown et al. [30] estimated that biomass, and thus carbon, in the forest would increase over the next 150 years for all forest types across the northern forest region (the states of Maine, New Hampshire, Vermont, and New York). However, northern hardwood–conifer forests in Maine were predicted to show the smallest increase in biomass, and to show little or no increase within the 30-year timeframe of this analysis. Their results also suggest that the increase in carbon storage is negatively impacted by increases in forest harvesting intensity and frequency. Nevertheless, their results suggest that estimates of the opportunity to store additional carbon in the forest through changes in management may vary greatly based on assumptions about the future carbon storage that will result from a continuation of current management trends.

Recent work from other regions indicates that the emphasis on managing forests for increased carbon storage is global, not regional [5,7,59,60]. Law et al. [59] found that net ecosystem carbon balance could be increased by 56% in Oregon from a combination of reforestation, afforestation, lengthened harvest cycles on private lands, and restricting harvest on public lands. China's forests are already a net carbon sink, but Chen et al. estimate that represents only 52% of the potential storage if rotation lengths were extended significantly [60]. There are a variety of NCS strategies for increasing carbon storage, the most useful of which for a given location will greatly depend on context [5,7]. The recent and dramatic increase in research and implementation of Natural Climate Solutions reflects a growing interest in using natural systems to mitigate climate change. Works similar to ours are necessary to elucidate local and regional opportunities, following from larger-, global-, or national-level studies [5,19,20].

4.2. Temporal Context

The scientific consensus at present is that global GHG emissions will need to reach net zero within about 30 years in order to limit global warming to a level that avoids the most extreme consequences of climate change [61]. While trees are long-lived organisms and foresters are often planning for a future they will not live to see, many of the carbon benefits of IFM in the Acadian Forest can be realized within 25 years. The importance of this latter contribution is gaining increased recognition:

> *"Climate scientists have quietly begun to converge on a stark conclusion: the window in which cutting emissions by reducing the use of fossil fuels alone can reverse climate change has essentially closed. To keep temperatures on the planet from rising 2 °C above preindustrial levels, the stated goal of the 2016 Paris Agreement, humanity will also have to swiftly develop ways to remove carbon from the atmosphere."* [62]

Our work here, as well as that of a growing list of scientific studies, demonstrates that IFM has the potential to remove large amounts of carbon from the atmosphere over the next 30 years. While details vary somewhat from one study to the next, the message is clear: forests have a greater capacity for climate mitigation than we are exploiting at present. As our work shows, this climate mitigation potential is not inconsistent with a continued use of the forest for wood products and other materials.

4.3. Economic Context

The potential for increasing carbon storage in the Acadian Forest is clear. However, since most of this landscape is in private ownership, and most of the additional carbon storage potential is on private lands, whether or not this potential is realized depends on the willingness of forest landowners to expand implementation of silvicultural practices known to increase carbon storage. This will require a significant departure from silviculture as commonly practiced in this region [29,35]. Because existing practices for valuing land when it is sold are focused on the value of merchantable timber at the time of sale rather than future value as timber matures, shifting to more active silviculture will in turn require holding land for the long term to benefit from practices such as precommercial and early commercial thinning.

Our financial modeling results indicate that EF is almost certainly less profitable in conventional terms (discounting future returns) than management focused on maximizing NPV, if the only source of revenue is timber returns and not sales of conservation easements or carbon credits. Work at the Penobscot Experimental Forest in Bradley, Maine confirms this conclusion: in a 65-year study, Granstrom et al. [63] compared a selection harvest system similar to the thinning recommended in EF to a fixed diameter-limit system similar to what is commonly practiced by some short-term landowners in Maine. The discounted value of the harvests from the diameter-limit system was higher (USD 1223 vs. USD 961 per hectare at a discount rate of 4%), but the selection system resulted in higher residual stand volume and value, with larger and higher-quality trees and a much lower proportion of unmerchantable growing stock [63]. The stand managed with selection harvest was nearly twice as valuable as the diameter-limit stand after 65 years [64]. Combined with the results of our financial modeling, the implication is that management that meets the EF standards can be profitable, particularly if the non-timber benefits that forests provide can be monetized.

In recent years, society's willingness to pay for non-timber forest values has been growing. Our financial model reflects the potential for a landowner to monetize carbon storage and recreation directly (through sales of carbon credits and recreational leases), and to leverage other values, such as watershed protection, wildlife habitat, and aesthetic value, through sales of conservation easements and loans or capital investments from "impact" investors, who value the social and environmental impacts of their investments. Though it will not provide the same short-term returns as business-as-usual management, EF offers long-term rewards in terms of stand quality, future revenue potential, and silvicultural flexibility [64], the latter of which may be key for future climate adaptation.

Because the forest products industry is very important to the rural economy in northern New England—USD 8.5 billion in current value in Maine alone [65]—and because of the desire to avoid "leakage" of the benefits of increasing carbon storage in the Acadian Forest by simply shifting harvest to other locations, an important issue will be how to maintain harvest levels while implementing EF. Unless harvests can be shifted to stands not currently harvested, such as small-diameter and low-value stands, or lands not currently actively managed, implementing EF could lead to lower harvest volumes, at least initially.

Our modeling indicates that implementing EF in areas with low stocking in place of management to maximize NPV could lead to as much as 120 m^3 ha^{-1} less total volume harvested over the first two decades, with most of this (95 m^3 ha^{-1}) being pulpwood. Some sawtimber harvest will also be forgone in the initial implementation of EF, though EF begins to produce higher volumes of sawtimber than management to maximize NPV as soon as year 20 of the modeling period. This represents forgone harvest in relation to the alternative management modeled, and not in relation to actual recent harvest levels. Nevertheless, implementing EF is likely to result in reduced harvest levels for the first two to three decades following the shift in management. Making up this harvest deficit in the early decades is extremely important, and it would involve shifting harvests to smaller-diameter stands that are overstocked and to landowners, e.g., family forest owners, that have not actively managed their lands previously. This will be a difficult but not impossible task, particularly if new markets for small-diameter and low-value wood can be developed. For example, a wood fiber insulation plant being built at present in Madison, Maine will use small-diameter wood and lumber byproducts, which should make stand improvement thinnings, such as those recommended in EF, more financially attractive. Other efforts to productively use small-diameter and low-value wood are also underway. Increased harvest from lands that are presently unmanaged may be achieved if smaller landowners can come to see practicing good management as socially and environmentally responsible.

4.4. Forest Management and Ecological Implications

While the need for climate mitigation, including enhanced contributions from forests, is urgent, forests also provide other ecosystem services that are highly valued by society. These include services such as water quality protection, recreational values, and wildlife habitat, among others. EF emphasizes these values alongside carbon storage, meaning that management is optimized to serve all these goals [38]. In particular, EF management is intended to address many of the gaps identified in [36], thus improving habitat values for a wide range of native wildlife species.

The present work also has implications for forest managers working in the Acadian Forest region. The implementation of EF standards could result in lower sawlog production in the near term, but higher sawlog production in the long term, implying a change in management regimes across the Acadian Forest in the coming decades. Potential to make up for the near-term reduction in wood production exists if forest managers are able to focus more on neglected lands that have not been managed in recent decades. The willingness of landowners and land managers to shift harvests in the near term will be determined by the ability of science and policy experts to make a compelling case for the longer-term benefits e.g., [5,12,29,38]. While making up for the shortfall in near-term timber harvests and mitigating any potential leakage are beyond the scope of the present study, they should be the focus of future work [19].

4.5. Conclusions

The primary goals of this study were to determine the amount of unrealized mitigation available from IFM in the Acadian Forest ecosystem and demonstrate how this mitigation can feasibly be attained. We used growth and yield modeling to assess the impacts of IFM on carbon storage in the Acadian Forest of the northeastern U.S. Practices applied in our modeling are enumerated in the Exemplary Forestry standards articulated by the New England Forestry Foundation [38]. Our study demonstrates that IFM practices have the potential to increase carbon storage in this region by 488 Tg, enough to contribute more than 20% of the region's 2050 emissions reduction goals. The financial modeling we've employed shows one potential way that IFM could be funded, through the combination of income from carbon markets, philanthropic conservation easements, timber harvesting, and capital investment. Our results add to the body of evidence demonstrating that the capacity of managed forests to mitigate carbon emissions has not been fully realized.

Our analysis indicates that IFM has the potential to substantially increase the contributions of forests to mitigating climate change by increasing carbon storage in this region while also managing for other forest values, and that there are approaches that can make IFM financially feasible in the current policy environment. This adds to the growing evidence that forest management has a role to play in climate change mitigation approaches that may rival or even surpass other forest-related strategies, such as tree planting [5,20]. However, as discussed in the Introduction, carbon storage is only one aspect to forests' influence on climate, and the interplay of all the different ways that forests influence climate may vary greatly by region and forest type. We suggest that similar analyses—and ones investigating forest influences on climate forcing agents other than carbon—be undertaken in the other forest regions in the U.S. and around the world to document the broader opportunities to use forests to mitigate climate change. While there are undoubtedly opportunities to increase carbon storage in other forests (not only those primarily affected by timber management, but also those impacted by wildfire, insects and disease, storm damage, etc.), the mitigation opportunities in other regions could be quite different and may focus on noncarbon pathways of forest influence on climate—e.g., albedo [16,17], BVOCs [15,66], or combinations of influences [15,19,67,68]—but all these contributions are important. For example, Rotenberg and Yakir [14] calculated that, in parts of the Middle East, loss of forests had already reduced global temperature increase by 0.2 °C because darker forest vegetation not only increased the absorption of incoming solar radiation, but also interfered with re-radiation of the heat absorbed.

The point is that forests offer us a very significant opportunity to address the existential threat we face from climate change. While we clearly need to eliminate emissions, we also need to remove CO_2 from the atmosphere, reflect more incoming solar radiation back into space, and increase transmission of longwave radiation into space [61]. Forests can help on all these fronts, and unlike many other proposed schemes to mitigate climate change, we know how to manage forests.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13122031/s1, Supplementary Materials SA: Exemplary Forestry Growth and Yield Modeling; Supplementary Materials SB: Northern New England Timber Price Analysis; Supplementary Materials SC: Simplified Financial Model; Supplementary Materials SD: Detailed Financial Model.

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Appendix A

Table A1. Carbon storage opportunity per hectare and total carbon storage opportunity on privately owned timberland in the Acadian Forest of New England, by county. “Carbon gap” is the difference between average carbon storage per hectare of private timberland in the Acadian Forest and average carbon storage per hectare expected under EF in the Acadian Forest, based on the results of modeling in the Mountains of the Dawn region.

State	County	Mg ha^{-1} CO_2e on Private Timberland, Excluding Soil Carbon	Carbon Gap, Mg ha^{-1} CO_2e	Privately Owned Forestland in the Acadian Forest Region, ha	Total Opportunity, Million Mg CO_2e
Maine	Aroostook	318	94.9	1,453,944	138.0
	Franklin	331	82.0	326,819	26.8
	Hancock	351	62.1	288,263	17.9
	Knox	345	67.5	31,554	2.1
	Lincoln	391	21.8	19,086	0.4
	Oxford	348	64.8	219,749	14.2
	Penobscot	333	79.2	597,994	47.4
	Piscataquis	330	82.3	833,034	68.6
	Sagadahoc	394	18.5	18,136	0.3
	Somerset	302	110.3	734,675	81.0
	Washington	306	106.5	561,807	59.9
New Hampshire	Coos	329	83.2	277,381	23.1
Vermont	Caledonia	376	36.5	88,192	3.2
	Essex	360	52.3	80,647	4.2
	Orleans	406	6.5	127,977	0.8
Total					488.0

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