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Rehabilitation forestry and carbon market access on high-graded northern hardwood forests

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Abstract: Decades of heavy-cutting and high-grading in the northeastern United States provide an opportunity for rehabilitation and increased carbon stores, yet few studies have examined the feasibility of using carbon markets to restore high-graded forests. We evaluated the effectiveness of rehabilitation on 391 ha of high-graded forest in Vermont, USA. Thirteen silvicultural scenarios were modeled over 100 years using the Forest Vegetation Simulator. Carbon offsets were quantified with the Climate Action Reserve (CAR) and American Carbon Registry (ACR) protocols and evaluated under voluntary and regulatory carbon price assumptions. Results indicate that management scenarios involving no harvest or low-intensity harvest yield the greatest incentives, yet these scenarios include a range of short-term rehabilitation options that provide flexibility for landowners. The choice of protocol also significantly influences results. Although ACR consistently generated more offsets than CAR for the same scenarios ($p < 0.05$), the protocols yielded similar net present values of US\$121–US\$256·ha^{-1} under high offset price assumptions. These returns are comparable to those generated from timber harvest alone under more intensive management scenarios. While timber will continue to be a primary source of revenue for many landowners, carbon markets may increasingly appeal as a new incentive for restoring high-graded forests.

Key words: restoration, rehabilitation silviculture, forest carbon, carbon markets, high-graded timberlands.

Résumé : Des décennies de coupe intensive et d'écrémage dans le nord-est des États-Unis fournissent une occasion de rétablir et d'augmenter les stocks de carbone, mais peu d'études ont examiné la possibilité d'utiliser les marchés du carbone pour restaurer les forêts écrémées. Nous avons évalué l'efficacité de mesures de rétablissement sur 391 ha de forêt écrémée dans le Vermont, aux États-Unis. Treize scénarios sylvicoles ont été modélisés sur plus de 100 ans à l'aide du Simulateur de végétation forestière. Les crédits de carbone ont été quantifiés à partir des protocoles de la Climate Action Reserve (CAR) et de l'American Carbon Registry (ACR) et évalués en assumant un prix du carbone établi de façon volontaire ou par réglementation. Les résultats indiquent que les scénarios d'aménagement n'impliquant aucune coupe ou des coupes de faible intensité produisent les meilleures perspectives de gains. Ces scénarios comportent plusieurs options de rétablissement à court terme qui donnent de la flexibilité aux propriétaires. Le choix du protocole a aussi une influence significative sur les résultats. Bien que le protocole ACR génère systématiquement plus de crédits que le CAR pour les mêmes scénarios ($p < 0{,}05$), les deux protocoles produisent des valeurs actualisées nettes similaires variant de 121 à 256 US\$ à l'hectare en assumant un prix des crédits de carbone élevé. Ces rendements sont comparables à ceux qui sont générés par la coupe forestière seulement dans le cadre de scénarios d'aménagement plus intensifs. Bien que le bois continue d'être la principale source de revenus pour de nombreux propriétaires, les marchés du carbone peuvent représenter des perspectives de gains de plus en plus attrayantes pour rétablir les forêts écrémées. [Traduit par la Rédaction]

Mots-clés : restauration, sylviculture de rétablissement, carbone forestier, marchés du carbone, forêts écrémées.

1. Introduction

Forest conservation and management are increasingly regarded as a means of reducing greenhouse gas (GHG) emissions. While forests are currently a net carbon sink globally (Pan et al. 2011), they continue to face pressure from unsustainable logging and conversion to nonforest uses. Worldwide, forest-based disturbances are the second largest source of global anthropogenic GHG emissions after fossil fuel combustion (Werf et al. 2009). In the northeastern United States (US), roughly half of the productive timberland is less than fully stocked due to past management and land use history (Hoover and Heath 2011). If all of the understocked forests in the northeastern US were restored to full stocking, they could store an additional 453 Tg of total aboveground live carbon, with the most poorly stocked lands providing the greatest capacity for increased carbon storage (Hoover and Heath 2011). While there is significant interest in using forest restoration for climate change mitigation, uncertainty remains over which management practices to implement and how to make them economically viable (D'Amato et al. 2011). The purpose of this study is to investigate the carbon storage potential of restorative silvicultural scenarios and to determine whether carbon markets can incentivize rehabilitation of overharvested, poorly stocked forestland.

1.1. Forest degradation and rehabilitation

In the northeastern US, the practice of high-grading was prevalent in the last few decades of the 20th century due to increased

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demand for high-quality hardwoods and the maturation of second-growth forest (Nyland 1992). High-grading or diameter-limit cutting involves preferentially removing the largest and most valuable trees in a stand without regard to future forest composition or productivity. Residual trees tended to be of poor quality and low vigor, with irregular, patchy distribution (Kenefic et al. 2005). In this paper, we use the term rehabilitation to describe a moderate level of silvicultural intervention employed to assist forest recovery (Stanturf and Madsen 2005). Specific proposals to rehabilitate high-graded forests in the northeastern US include removing trees of poorest quality, regenerating desirable species, controlling competition, and concentrating growth on the best trees in a stand. In some cases, landowners might clear the stand to regenerate new trees of improved value and vigor. Most of these methods require significant up-front investment with benefits accruing many decades in the future (Kenefic and Nyland 2005).

1.2. Carbon market potential

Studies indicate that there is significant potential to increase carbon storage in temperate forests, thereby reducing atmospheric GHG concentrations and contributing to climate change mitigation (Malmsheimer et al. 2008; Charnley et al. 2010; Hoover and Heath 2011). Forest carbon markets have garnered significant public and political interest as a potential source of revenue to landowners for sustainable forest management (Malmsheimer et al. 2008). The currency of the forest carbon market is an “offset,” which is the avoidance or removal of 1 tonne (t) of carbon dioxide equivalent (CO_2e) used to compensate for the emission of 1 t of CO_2e.

Globally, more than 90% of forest carbon offsets are traded in the voluntary carbon market at a total value of $178 million (US dollars used throughout) in 2010 (Diaz et al. 2011). However, regulatory markets comprise the vast majority of total carbon transactions and were valued at $142 billion in 2010 (Linacre et al. 2011). At the time of this study, the only regulatory market to allow forest offsets from a range of activities — urban forestry, reforestation, avoided conversion, and improved forest management — is California's state-level cap and trade system. We selected the improved forest management activity for evaluation because it is most consistent with rehabilitation. The American Carbon Registry (ACR), the Climate Action Reserve (CAR), and the Verified Carbon Standard (VCS) all have improved forest management methodologies for generating carbon offsets; however, we chose ACR and CAR for this analysis because they comprise the bulk of the forest carbon supply in the US (Diaz et al. 2011).

Despite substantial and increasing interest in forest carbon offsets, a number of practical barriers impede broader landowner participation such as high initial start-up costs, long time commitments, and uncertain future demand (Fletcher et al. 2009; Charnley et al. 2010; Dickinson et al. 2012). Early experience with forest carbon projects suggests that transaction costs for developing and maintaining a project can be high (Yonavjak et al. 2011). While cost is a critical factor, a number of studies have found the type of accounting methodology to be an even greater determinant of overall project viability (Pearson et al. 2008; Foley et al. 2009; Galik et al. 2012).

To date, only a handful of studies have examined carbon offset potential using empirical forest inventory data and accepted carbon accounting methodologies. To our knowledge, none has focused specifically on high-graded, poorly stocked forests. It thus remains unclear how these forests will fare in emerging carbon markets. Will low stocking be an advantage because it provides greater potential for additional carbon storage or will it be a disadvantage because of unfavorable starting conditions and the longer time period necessary to increase stocking?

There also continues to be active debate in the scientific literature around which forest management approaches are most effective at reducing CO_2 emissions. Some studies suggest that frequent and intense harvests are more effective at reducing CO_2 emissions through the substitution of wood products for more carbon-intensive building materials (Perez-Garcia et al. 2005; Eriksson et al. 2007). Others suggest that lower intensity management is more effective at reducing CO_2 emissions, even when accounting for wood products, because more carbon is stored onsite in forest carbon pools (Harmon and Marks 2002; Nunery and Keeton 2010). Few studies have specifically tested the effects of rehabilitation forestry on carbon dynamics. Thus, uncertainty remains around which methods are most effective at restoring forest productivity and carbon storage on high-graded, poorly stocked forests.

To address this gap in the literature, we considered two questions: (1) how do restorative silvicultural scenarios impact carbon storage on high-graded forests in the northeastern US, and (2) what challenges and opportunities do high-graded forests face in accessing carbon markets? We hypothesized that lower intensity management would improve stand structure and yield greater carbon stores than higher intensity management. We also expected that despite up-front and ongoing transaction costs, certain rehabilitation scenarios would generate net positive returns from the sale of offset credits. The results of this study have implications for millions of hectares of understocked forestland across the northeastern US and could inform ongoing discussions in the US and globally around the use of market-based mechanisms in forest restoration efforts.

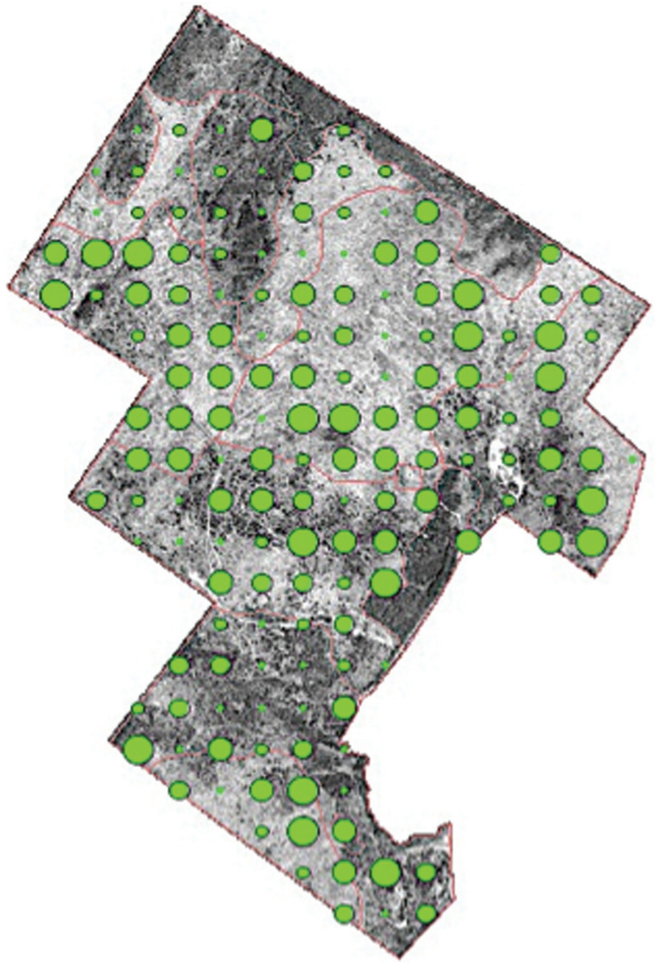
2. Methods

2.1. Study area

This study used data from 391 ha of privately owned northern hardwood forest in northeastern Vermont, USA (Victory: 44°33′8.28″N, 71°51′54.21″W). The property is located within the larger Northern Appalachian–Acadian ecoregion, which stretches from New York in the west to Nova Scotia, Canada, in the east. The topography of the study area ranges from 426 to 823 m in elevation, with predominantly southern aspects. Soils are primarily deep to moderately deep, well-drained Tunbridge–Lyman complex and Monadnock fine sandy loam. The land is moderately productive, with a site class of II–III and a site index of 15–18 m for a 50-year-old sugar maple (*Acer saccharum* Marsh.). The dominant species by basal area (BA) are *A. saccharum* (31%), *Betula alleghaniensis* Britt. (yellow birch; 16%), and *Fagus grandifolia* Ehrh. (American beech; 14%), with smaller components of *Abies balsamea* (L.) Mill. (balsam fir; 11%), *Acer rubrum* L. (red maple; 8%), *Betula papyrifera* Marsh. (paper birch; 6%), and *Picea rubens* Sarg. (red spruce; 4%).

This study site was selected because of its land use history and current condition, which is dominated by low stocking, altered species composition, and poorly formed, unmerchantable trees. This condition is representative of similarly cutover forestland across the northeastern US (Nyland 1992; Kenefic et al. 2005). The majority of trees on the Victory property are in either the sapling or pole size classes, and almost half of the trees above 11.4 cm are considered unacceptable for merchantable timber. Compared with typical northern hardwood stands of low productivity in the White Mountain region of eastern Vermont and western New Hampshire, which contain an average of 21 m^2 basal area·ha^{-1} and 18.5 m^3 sawlog volume·ha^{-1} (Climate Action Reserve 2010), Victory contains an average of 12 m^2 basal area·ha^{-1} and 4.7 m^3 sawlog volume·ha^{-1}. While average aboveground live carbon for northern hardwood forests in the White Mountain region is 46 Mg·ha^{-1} (Climate Action Reserve 2010), Victory contains an average of 24 Mg aboveground live carbon·ha^{-1}. Due to the variable nature of past harvesting at Victory, current carbon stores are highly irregular, ranging from a low of 0 to a high of 97 Mg C·ha^{-1} across the property (Fig. 1).

Fig. 1. Variability in average carbon stores on the Victory property as calculated in the starting year, 2012. Circle sizes represent plot-level estimates of CO_2e in tonnes per hectare that is stored in aboveground live trees. Estimates are spatially accurate at the stand level.



2.2. Data collection and analysis

A forest inventory was conducted in 2008 per the standards of the CAR Forest Project Protocol v. 2.1. Data were collected from a systematic grid of 157 variable-radius plots using a 2.3 metric basal area factor prism. Plots were stratified across four stands, ranging in size from 30 to 246 ha, based on forest composition and structure. At each plot, data were collected on species, diameter at breast height (DBH, measured at 1.3 m), canopy position, and the sawlog potential of each standing live or dead tree greater than 11.4 cm DBH. For standing dead trees, a decay stage between 1 and 9 was assigned following Sollins et al. (1987). Forest type, site class, site index, slope steepness, and aspect were recorded at each plot.

After the 2008 forest inventory, revisions were made to the CAR protocol requiring the component ratio method (CRM) to estimate tree biomass rather than the national allometric equations developed by Jenkins et al. (2003) (Climate Action Reserve 2010). The CRM uses regionally specific volume equations, most of which require tree height as inputs (Russell-Roy 2012). To add height data to the 2008 inventory, a stratified random sample of 20% of the original plots from each stand was re-measured in 2011. Data on tree species, height, and DBH were also recorded at each plot to create species-specific height–diameter functions using nonlinear least squares regression. After testing accuracy of fit and determining the equations to be robust, we used these functions to predict tree heights for the rest of the living and structurally sound dead trees in the 2008 inventory (Russell-Roy 2012). For highly decayed snags and standing dead trees with broken tops, height was not strongly correlated with DBH; therefore, average heights were calculated by decay class from an extensive data set of northern hardwood forest measurements collected at 35 sites across Vermont, New York, and New Hampshire (Littlefield and Keeton 2012).

2.3. Rehabilitation modeling

Using Victory's updated forest inventory data, we modeled the growth of existing trees from 2008 to 2012, which was the starting year of our analysis. Of 157 total plots, two were removed from the analysis because they fell on log landings where trees might not follow expected growth patterns. We modeled different elements of passive restoration, intermediate treatment (i.e., thinning), and regeneration harvesting to form 13 distinct rehabilitation scenarios comprising a spectrum of management intensity. These scenarios were grounded in practices widely used in northern hardwood forests (Leak et al. 1987; Nyland 2007), yet each practice was tailored to maintain higher than average stocking, restore desirable species, and improve stand structure.

We modeled three possible initial activities, two possible intermediate activities 40 years into the simulation, and four possible regeneration activities 80 years into the simulation. Initial rehabilitation activities consisted of (*i*) an immediate silvicultural clearcut in 2012 to regenerate the stand, (*ii*) a targeted free thinning in 2022 to improve stand structure and composition, or (*iii*) a period of recovery in which no harvesting occurs. These initial activities were followed 40 years later by intermediate treatments of either (*i*) thinning from below or (*ii*) no thinning. These intermediate treatments were followed in another 40 years by one of four regeneration options: (1) a clearcut, (2) an irregular shelterwood harvest, (3) an individual tree selection (ITS) harvest, or (4) no harvest. In addition to these 13 possible rehabilitation scenarios, a "business as usual" scenario of continued high-grading was also modeled (Table 1).

2.4. Growth and yield model description

Each of the 13 rehabilitation scenarios was modeled for 100 years, from 2012 to 2112, using the Northeast variant of the Forest Vegetation Simulator (FVS). FVS is an empirical, individual tree based growth and yield model developed by the USDA Forest Service (Dixon 2002). The model has been approved for use by both CAR and ACR protocols and is widely used in modeling studies that compare future management alternatives (e.g., Nunery and Keeton 2010). Because FVS is distance-independent, it cannot fully implement a spatially explicit silvicultural treatment such as a crop tree release (CTR) (Miller et al. 2007). Because CTR is one method that has been proposed to restore high-graded stands in the northeastern US (Kenefic and Nyland 2005), we simulated a comparable type of improvement cut by targeting short-lived and noncommercial species for removal within the 5.0–30.5 cm DBH range (Table 1).

Unlike some regional variants, the Northeast variant of FVS does not contain a natural seed-based regeneration submodel. We developed regeneration inputs based on the species composition of the property, the shade tolerance of each species, and the intensity of the management scenario applied (Russell-Roy 2012). Because FVS can be sensitive to small changes in regeneration assumptions (Hoover and Rebain 2011), all model outputs were carefully checked to confirm that predicted growth rates were within published ranges for northern hardwood forests (Leak et al. 1987; Leak and Gove 2008).

Carbon estimates were generated from the Fire and Fuels Extension (FFE) of FVS (Rebain 2010). FFE calculates tree biomass similarly to the component ratio method when regional equations are selected (Russell-Roy 2012). Carbon was calculated in

Table 1. Description of management treatments modeled in the Forest Vegetation Simulator (FVS).

Treatment	
Free thin	
Goal	Stand improvement
Schedule	Early treatment
	10 years after start date
Parameters	Remove trees between 5 and 30.5 cm DBH
	Target species to cut:
	Populus tremuloides
	Populus grandidentata
	Betula papyrifera
	Fagus grandifolia
	Acer pensylvanicum
	Prunus pensylvanica
Thin from below	
Goal	Stand improvement
Schedule	Intermediate treatment
	40 years after free thin
Parameters	Remove smallest trees first to BA of 18 $m^2 \cdot ha^{-1}$
	Target species to leave:
	Acer saccharum
	Betula alleghaniensis
	Prunus serotina
	Picea rubens
	Picea glauca
	Pinus strobus
Clearcut	
Goal	Even-aged regeneration
Schedule	100-year rotation
Parameters	All trees removed down to 5 cm DBH
	Slash removed from site
Irregular shelterwood	
Goal	Even-aged regeneration
Schedule	100-year rotation
Parameters	Residual BA of 11.5 $m^2 \cdot ha^{-1}$
	Smallest DBH removed: 10 cm
	Removal cut 10 years later
	Smallest DBH removed: 15 cm
	Number of permanently retained trees$\cdot ha^{-1}$: 25
	Slash retained on site
Individual tree selection	
Goal	Uneven-aged regeneration
Schedule	30-year cutting cycle
Parameters	Q-factor: 1.3
	Residual BA of 19 $m^2 \cdot ha^{-1}$
	Minimum DBH class: 5 cm
	Maximum DBH class: 61 cm
	DBH class width: 5 cm
	Number of legacy trees$\cdot ha^{-1}$: 12
	Average DBH of legacy tree: 41 cm
	Slash retained on site
High-grading (i.e., thin from above)	
Goal	Remove largest trees first
Schedule	Whenever BA exceeds 20.7 $m^2 \cdot ha^{-1}$
Parameters	Residual BA of 9 $m^2 \cdot ha^{-1}$
	No DBH range
	Slash retained on site

standing live trees, standing dead trees, and harvested wood products (both in use and in landfill), which are the carbon pools required by CAR and ACR for improved forest management projects (Table 2). Soil carbon is an optional pool in the CAR protocol and excluded in the ACR protocol due to issues of uncertainty and measurement difficulty (Schwenk et al. 2012). All required carbon pools were selected from FFE's fuel reports, carbon reports, and harvested products reports at 10-year time steps and exported to Microsoft Excel for analysis.

2.5. Quantifying carbon offsets

Baseline is a critical component of carbon offsets because it establishes the reference condition against which the project activity is compared. A scenario of ongoing high-grading was selected as the baseline for CAR because (*i*) it is a continuation of past management, (*ii*) it is legal under current laws and regulations, and (*iii*) it is still widely practiced across the region. This baseline could not be used for ACR because of requirements that baselines must (*i*) maximize the net present value (NPV) of harvested wood products over 100 years at a 5% annual discount rate and (*ii*) consist of practices that are recommended by state or federal agencies (American Carbon Registry 2011). Because a high-grading scenario does not meet these criteria, the scenario involving an initial clearcut, followed by a thinning from below, followed by a regeneration clearcut on a 100-year rotation (Clear_Thin_Clear) was selected as the baseline for ACR as it maximizes NPV and involves a standard commercial, even-aged silvicultural system. While using two different baselines might seem like an inconsistency, this study is interested in comparing offset credits as they are quantified under accepted forest protocols.

Both the CAR and ACR protocols require that offset credits be calculated from a single property-wide carbon estimate; however, these calculations do not provide an estimate of variance. To address this issue, we calculated offset credits at both the plot level and the property level. This allowed us to statistically compare results and also determine whether results differ based on the scale of analysis.

2.6. Assessing outcomes

Economic conditions were evaluated by comparing the costs of conducting rehabilitation treatments and developing, monitoring, and verifying a carbon project over time, with revenues from the sale of wood products and carbon offset credits. Carbon offset revenues were analyzed under three sets of price assumptions: (1) low prices in the voluntary market, (2) high prices in the voluntary market, and (3) high prices in California's regulatory market (Table 3). Regulatory prices apply only to the CAR protocol at this time, as this protocol was adopted for use in California's cap and trade system with slight modifications (Air Resources Board 2010). Offset costs and revenues were based on a combination of market literature (Point Carbon 2011; Yonavjak et al. 2011) and expert opinion (C.D. Kerchner and J.S. Gunn, personal communication, 2012). Timber harvest costs and revenues were based on the professional judgment of foresters actively working in the study area (Redstart Forestry, personal communication, 2012). All net values were discounted to the present at a 5% annual rate for 100 years using equations provided in Davis et al. (2000). For consistency, we assumed that ACR projects were voluntarily extended for 60 years beyond the 40-year minimum commitment period, whereas CAR projects lasted for the minimum commitment period of 100 years (although monitoring and verification of CAR credits continued for another 100 years, per protocol requirements) (Table 2).

We measured response variables in four key categories: (1) forest structure (mean DBH and sawlog volume), (2) carbon storage, (3) offset credits, and (4) NPV, discounted at a 5% annual rate. Comparisons were made using repeated-measures ANOVA in JMP (version 9; SAS Institute Inc.). We used the Shapiro–Wilk test to determine whether data distributions were normal or nonnormal. For normal data, we used the parametric version of repeated-measures ANOVA. For nonnormal data, we performed a rank transformation procedure to standardize the data (Conover and Iman 1981; Thompson and Ammann 1990) and then used repeated-measures ANOVA. For cases in which we analyzed a single

Table 2. Comparison of the American Carbon Registry (ACR) and Climate Action Reserve (CAR) improved forest management protocols.

	ACR	CAR
Project type	Improved forest management	Improved forest management
History	Methodology for nonfederal US forestlands, developed by Columbia Carbon LLC; released September 2011	Version 3.2, developed by CAR workgroup; released August 2010
Eligibility	No minimum acreage; limited to US; certified through FSC, SFI, or ATFS within 1 year of start date	No minimum acreage; limited to US; certified through FSC, SFI, or ATFS, or other sustainability criteria
Required carbon pools	Above- and below-ground standing live wood, aboveground standing dead wood (unmanaged stands), harvested wood products	Above- and below-ground standing live wood, above- and below-ground standing dead wood, harvested wood products
Optional carbon pools	Aboveground standing dead wood (managed stands), lying dead wood	Lying dead wood, shrubs and herbaceous understory, litter and duff, soil
Excluded carbon pools	Belowground standing dead wood, litter and forest floor, soil	None[a]
Carbon accounting method	CRM[b] for live and sound dead trees; volumetrically for highly decayed dead trees; carbon in wood products at end of 100 years based on 1605(b) method	CRM[b] for live and sound dead trees; volumetrically for highly decayed dead trees; average carbon in wood products over 100 years based on 1605(b) method
Project activity	Increase carbon relative to baseline and include commercial timber harvest under a forest management plan	Increase or maintain carbon relative to baseline; commercial timber harvest is not required
Baseline activity	Legal scenario that maximizes NPV; annual values used until 20-year average is reached	Business as usual scenario averaged over 100 years relative to FIA mean for the project's assessment area
Minimum project length	40 years (two 20-year crediting periods)	100 years after the last carbon offset is issued
Permanence	Risk mitigation to cover loss of carbon, including buffer pool, insurance, or other approved methods	Legally binding Project Implementation Agreement with CAR and buffer pool contribution based on risk assessment
Deductions	Leakage, uncertainty, risk of reversal or impermanence	Leakage, uncertainty, risk of reversal or impermanence
Sampling method	Permanent or temporary plots; stratification required if area is heterogeneous; inventory data no older than 10 years	Permanent or temporary plots; stratification not required; inventory data no older than 12 years

[a]Though CAR does not technically exclude any carbon pools, none of their optional pools (apart from soils) is currently eligible to generate offsets.
[b]CRM (component ratio method) is used by the U.S. Forest Inventory and Analysis program.

nonnormal response variable, we used a nonparametric Friedman's repeated-measures ANOVA in GraphPad Prism (version 5).

3. Results

3.1. Stand structure

Model results indicate that the choice of management has a significant effect on stand structure and related habitat characteristics, as quantified by quadratic mean diameter (QMD) and sawlog volume (Friedman's test, $p < 0.0001$). Overall, the no-management scenario (Recov_noHarv) achieves significantly higher QMD (15.7 ± 0.3 cm) and sawlog volume (108.8 ± 5.1 $m^3 \cdot ha^{-1}$) on average over the 100-year simulation period than all other scenarios (Dunn's multiple comparisons, $p < 0.05$). Other scenarios that improve stand structure combine either one of the three initial rehabilitation activities with a long-term strategy of no management or an initial period of recovery with a long-term strategy of management that retains greater amounts of structure such as individual tree selection (ITS) or irregular shelterwood (IrSh) harvests (Fig. 2; Table 4). While many management scenarios can improve the structural characteristics of degraded forests, these results support our hypothesis that lower intensity management restores significantly greater proportions of large, commercially viable trees than more intensive management.

3.2. Carbon storage

Forest carbon dynamics are highly influenced by management practices over time (Fig. 3). Average carbon stores over the 100-year simulation period in standing live, standing dead, and harvested wood product carbon pools differ significantly across management scenarios (Freidman's test, $p < 0.001$), with no-management and low-intensity management scenarios storing the most carbon on average (Table 4; Fig. 4). The no-management scenario (Recov_noHarv) yields the highest average carbon storage at 94.2 ± 2.5 $Mg \cdot ha^{-1}$ and is not significantly different from the scenario involving an initial regeneration clearcut followed by no harvest (Clear_noHarv) at 90.0 ± 0.4 $Mg \cdot ha^{-1}$. Other scenarios involving either an initial period of recovery or a long-term strategy of no harvest also yield high average carbon stores

Table 3. Cost and revenue assumptions used in calculations of net present value.

Costs	ACR	CAR	Frequency
Project development ($ per project)			
Project development	50 000	50 000	Once
Membership/account setup	500	500	Once
Project submittal/screening	1000	500	Once
Account maintenance/renewal	500	500	Annually
GHG plan validation[a]	4000	—	Each crediting period
Account closing	150	—	Once
Desk verification	4 000	4 000	Annually
Ongoing project management	5 000	5 000	Annually
Field verification[a]	16 000	16 000	Every 5 years for ACR; every 6 years for CAR
Offset administration ($·t CO_2e^{-1})			
Credit issuance/activation	0.15	0.20	When credits are verified
Credit retirement	0.02	—	When credits are sold
Field inventory costs ($·ha^{-1})			
Forest inventory[a]	33	33	Every 10 years for ACR; every 12 years for CAR
Forest management costs ($·ha^{-1})			
Marked forestry	128	128	When thinning, ITS, or shelterwood occurs
Unmarked forestry	64	64	When clearcut or shelterwood removal occurs
Revenues	**ACR**	**CAR**	**Frequency**
Carbon offset sales ($ per credit)[b]			
Low voluntary			
2012–2014	8.50	8.50	When credits are sold
2015–2020	10	10	When credits are sold
2021–2100	12	12	When credits are sold
High voluntary			
2012–2014	10	10	When credits are sold
2015–2020	15	15	When credits are sold
2021–2100	30	30	When credits are sold
Regulatory			
2012–2014	—	11	When credits are sold
2015–2020	—	26	When credits are sold
2021–2100	—	50	When credits are sold
Timber revenue ($·m^{-3})			
Pulp stumpage	3	3	When harvest occurs
Sawlog stumpage	42	42	When harvest occurs

Note: Values centered between the two columns for American Carbon Registry (ACR) and Climate Action Reserve (CAR) are the same for both ACR and CAR. GHG, greenhouse gas.

[a]We assume that costs will decrease over time. Thus, in subsequent years, we deduct 20% from the listed price for these costs.

[b]Offset revenues become costs when carbon credits are negative (i.e., a reversal occurs). We assume that offsets will be purchased in the same year and at the same price to compensate for a reversal.

between 78.1 and 85.3 Mg·ha^{-1} and are not significantly different from each other (Recov_ITS, Thin_Thin_noHarv, Recov_IrSh, and Clear_Thin_noHarv). Continued high-grading, on the other hand, yields significantly lower carbon storage than all other management scenarios at 51.1 ± 0.9 Mg·ha^{-1} (Table 4; Fig. 4). These findings support our hypothesis that lower intensity management results in higher levels of carbon storage.

3.3. Carbon credits after 100 years

As with stand structure and carbon storage, forest management decisions significantly affect the number of carbon credits that can be generated through improved forest management ($p < 0.0001$). However, the choice of offset protocol has a significant effect on the total number of eligible credits as well ($p < 0.0001$). Calculating credits under the ACR protocol consistently yields greater credits over a 100-year period than calculating credits under the CAR protocol, even for the same management scenarios (Fig. 5). This takes into account different baselines, as well as different deductions for uncertainty, leakage, and reversals (Table 5). While all scenarios generate significantly more carbon credits under ACR, the same five scenarios generate the greatest quantities of credits under both protocols (Fig. 5; Table 4). These top scenarios involve different initial rehabilitation activities but employ the same long-term strategy of either no harvest or ITS harvests.

Not all of the 13 rehabilitation scenarios modeled in this study are eligible to generate carbon credits under the ACR and CAR protocols (Fig. 5). Under ACR, the Clear_Thin_Clear scenario is not eligible because it involves the same management activities as the baseline. That it still generates a moderate amount of carbon credits is an artifact of averaging the baseline over each 20-year crediting period. Because the ACR protocol requires ongoing commercial timber harvesting, the Recov_noHarv scenario would not be an eligible offset project either, even though it would generate a large quantity of credits if allowed. CAR allows projects with no commercial management to participate but contains other requirements that prohibit projects from reducing aboveground live carbon below the baseline. As a result, all six scenarios involving either clearcuts or irregular shelterwood harvests as a long-term strategy would be ineligible to generate carbon credits under CAR (Fig. 5). To become eligible, these harvests would need to be carefully staggered across space and time so as to mute the severity of reductions in live aboveground carbon.

3.4. Carbon credits after 40 years

Over a shorter time period of 40 years (ACR's minimum project length), only the initial rehabilitation activities have a role in

Fig. 2. Stand structural metrics for each rehabilitation scenario, averaged over the 100-year simulation period. The shaded bars represent mean sawlog volume (in $m^3 \cdot ha^{-1}$), and the points (solid diamonds) represent quadratic mean diameter (QMD; in cm).

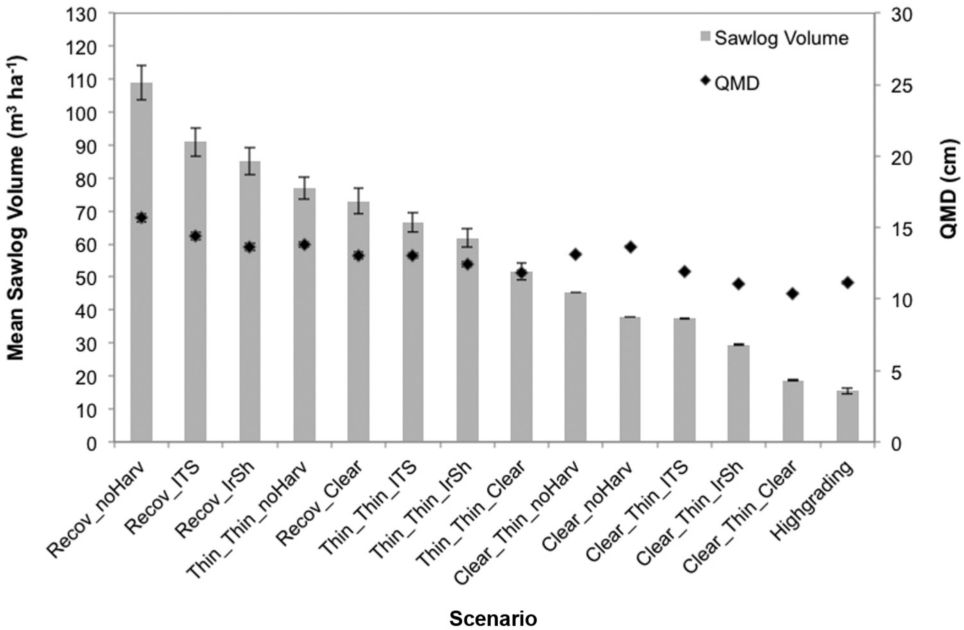


Table 4. Results of management scenarios on average stand structure, average carbon storage, and cumulative carbon credits over the 100-year projection period.

	Stand structure				Carbon storage		Carbon credits			
	QMD (cm)		Sawlog volume ($m^3 \cdot ha^{-1}$)		Carbon ($Mg \cdot ha^{-1}$)		ACR (t $CO_2e \cdot ha^{-1}$)		CAR (t $CO_2e \cdot ha^{-1}$)	
Management scenario	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
High-grading	11.2	0.1	15.5	0.9	51.1	0.9	—	—	—	—
Recover_noHarvest	15.7	0.3	108.8	5.1	94.2	2.5	339.1[a]	3.3	271.5	4.8
Recover_ITS	14.4	0.3	90.9	4.4	85.3	2.4	221.6	3.8	85.3	2.6
Recover_IrShelter	13.6	0.3	85.0	4.0	81.1	2.5	109.4	5.1	−38.0[a]	2.0
Recover_Clear	13.1	0.2	73.0	3.9	77.3	2.5	55.6	5.3	−90.1[a]	2.2
Thin_Thin_noHarvest	13.8	0.2	76.9	3.3	78.1	1.6	298.8	5.2	228.8	2.4
Thin_Thin_ITS	13.0	0.2	66.7	3.0	70.7	1.6	212.0	4.4	83.6	2.3
Thin_Thin_IrShelter	12.4	0.2	61.7	2.8	66.8	1.7	122.9	4.1	−31.4[a]	2.2
Thin_Thin_Clear	11.9	0.2	51.8	2.6	62.6	1.6	77.2	4.2	−93.1[a]	2.0
Clear_Thin_noHarvest	13.1	0.1	45.3	0.1	79.5	0.4	396.7	4.2	267.5	1.1
Clear_Thin_ITS	11.9	0.1	37.4	0.1	71.4	0.4	293.2	4.2	99.7	1.1
Clear_Thin_IrShelter	11.0	0.1	29.5	0.1	67.0	0.4	193.0	4.2	−46.4[a]	0.8
Clear_Thin_Clear	10.4	0.1	18.7	0.1	64.1	0.4	148.5[a]	4.3	−68.3[a]	1.0
Clear_noHarvest	13.7	0.1	37.9	0.1	90.0	0.4	329.6	4.2	265.5	1.1

Note: QMD, quadratic mean diameter; ACR and CAR, American Carbon Registry and Climate Action Reserve, respectively.
[a]These credits are hypothetical only, as the management scenarios are not technically eligible to generate carbon credits.

determining project outcomes. As with the 100-year calculations, both management scenario and offset protocol have significant effects on the generation of carbon credits, with ACR consistently generating more credits than CAR for the same scenarios ($p < 0.05$). Under ACR, the initial recovery and initial clearcut scenarios generate a statistically similar number of carbon credits after 40 years, largely due to the pulse of regeneration that is projected to occur after the clearcut. Under CAR, the initial clearcut scenario generates the most carbon credits, followed by the recovery and thinning scenarios, which are not significantly different from each other.

3.5. Plot vs. property scales

An unexpected result of this study is that total cumulative credits differ depending on whether they are calculated at the plot level or the property level. After 40 years, ACR's property-level carbon credit estimates do not differ substantially from the plot-level averages for the recovery or thinning scenarios (<3.0 t $CO_2e \cdot ha^{-1}$ difference); however, ACR's property-level estimate for the clearcut scenario is 15.8 t $CO_2e \cdot ha^{-1}$ higher than the plot-level average (Fig. 6*a*). Under CAR, the differences are more pronounced. CAR's property-level estimate is 26.9 t $CO_2e \cdot ha^{-1}$ lower for the recovery scenario, 30.3 t $CO_2e \cdot ha^{-1}$ lower for the thinning scenario, and 27.4 t $CO_2e \cdot ha^{-1}$ higher for the clearcut scenario than the plot-level averages of carbon credits for the same scenarios (Fig. 6*b*).

Similar patterns are also apparent after 100 years. Under the ACR protocols, the differences between property-level and plot-level estimates of carbon credits range from 0.1 to 17.0 t $CO_2e \cdot ha^{-1}$, depending on the management scenario (Fig. 6*c*). Under the CAR protocols, the differences between property-level and plot-level estimates of carbon credits are much larger, ranging from 0.7 to 99.6 t $CO_2e \cdot ha^{-1}$ (Fig. 6*d*).

Fig. 3. Trends in carbon storage over the 100-year projection period for the 13 rehabilitation scenarios plus the "business as usual" high-grading scenario.

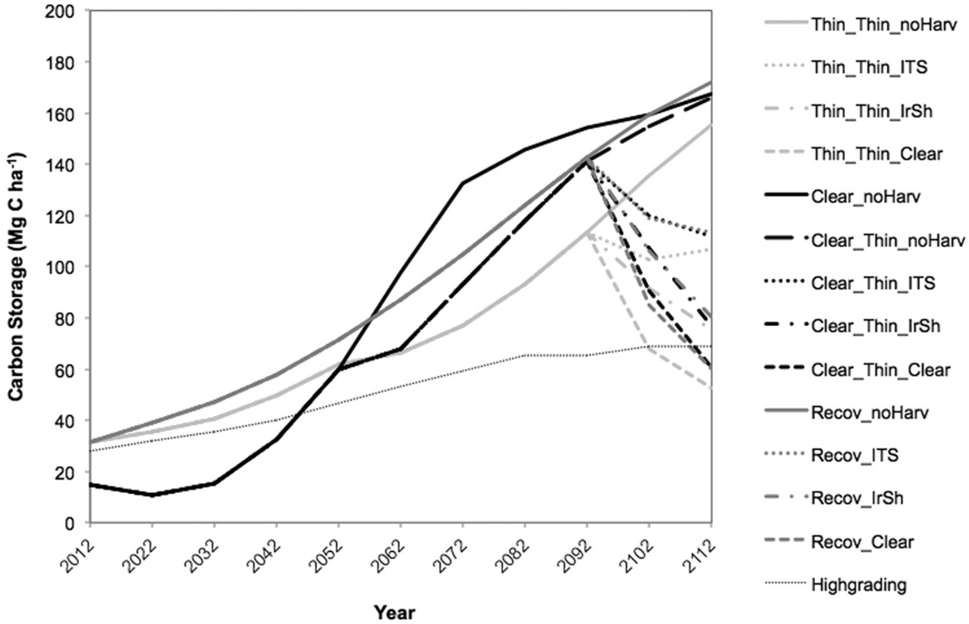
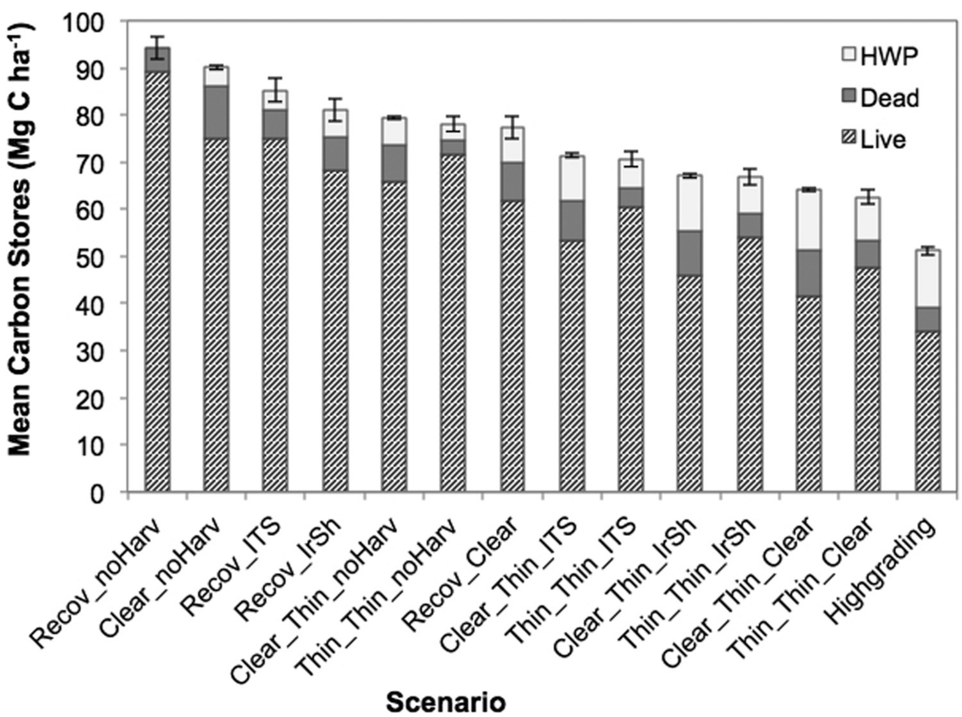


Fig. 4. Average carbon stores over 100 years in live tree, dead tree, and harvested wood product (HWP) carbon pools.



3.6. Net present value

With relatively low price assumptions for carbon credits in the voluntary market, starting at \$8.50·t CO_2e^{-1} in 2012 and rising to \$12·t CO_2e^{-1} after 2020, the NPV of carbon offset generation is highly negative. Thus, it costs more to develop, monitor, and verify a project than can be generated through the sale of carbon credits. This result is consistent across all eligible management scenarios and protocols (Fig. 7*a*). Two management scenarios are not eligible to generate carbon offsets under ACR, and six are not eligible under CAR. However, these scenarios generate positive NPV from the sale of harvested wood products alone. The two exceptions are (*i*) Thin_Thin_IrSh, which is not eligible to generate credits under CAR but also generates negative NPV from harvesting, and (*ii*) Recov_noHarv, which is not able to generate credits under ACR but does not involve any harvesting. The highest NPV comes from the Clear_Thin_Clear scenario, which is not eligible for carbon credits under either ACR or CAR but generates positive NPV of \$246 ± \$27·ha^{-1} over 100 years from harvesting alone (Fig. 7*a*). Similarly, the Clear_Thin_IrSh scenario is not eligible for carbon credits under CAR but generates positive NPV of \$238 ± \$27·ha^{-1} from harvesting alone. This scenario is eligible for carbon credits under ACR, and if a carbon project were to be pursued,

Fig. 5. Cumulative carbon credits after 100 years of project accounting under the CAR and ACR offset protocols. Bars with diagonal hatching indicate scenarios that are technically ineligible to generate carbon credits because they violate requirements of the protocols.

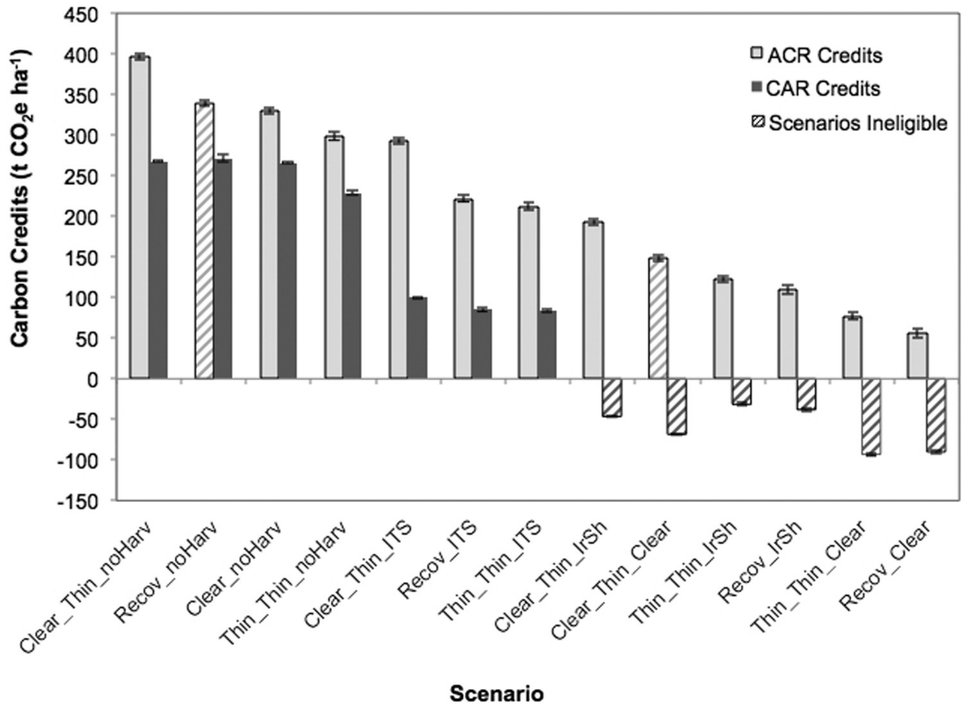


Table 5. Comparison of deductions required by the American Carbon Registry (ACR) and Climate Action Reserve (CAR) protocols for our study site.

Deductions[a]	ACR	CAR
Uncertainty	0%–20%[b]	5%
Risk of reversal or buffer pool contribution	15%	19%
Activity-shifting leakage	None assumed as the project must be certified	20% of the difference between actual and baseline carbon in harvested wood products (HWPs) (only when the difference is <0)
Market leakage	0%–40%[c]	20% of the difference between actual and baseline carbon in HWPs

[a]All deductions are applied to the annual calculation of greenhouse gas (GHG) reductions, unless otherwise noted.
[b]Depending on whether the project uncertainty is <10% of the mean at the 90% confidence level (0% deduction) or not (half-width of CI).
[c]Depending on whether reductions in total HWPs compared with baseline are <5% (0% deduction), <25% (10% deduction), or >25% (40% deduction).

total NPV would fall to –\$534 ± \$19·ha^{-1} due to the high up-front costs and low returns from the sale of offsets at these low price points (Fig. 7*a*).

With higher price assumptions for carbon credits in the voluntary market, starting at \$10·t CO_2e^{-1} in 2012 and rising to \$30·t CO_2e^{-1} after 2020, the NPV of carbon offsets is still substantially negative for all eligible management scenarios under CAR. The only positive revenue comes from the five scenarios that are ineligible to produce offsets but generate positive revenue from harvesting (Fig. 7*b*). With higher carbon prices, three management scenarios generate positive NPV from offsets under ACR. These scenarios involve an initial period of recovery and generate net returns of \$121–\$187 ± \$28·ha^{-1} from the sale of offsets alone. When timber revenue is included, total NPV increases to \$167 ± \$29·ha^{-1}, \$174 ± \$29·ha^{-1}, and \$210 ± \$29·ha^{-1} for the Recov_Clear, Recov_IrSh, and Recov_ITS scenarios, respectively (Fig. 7*b*).

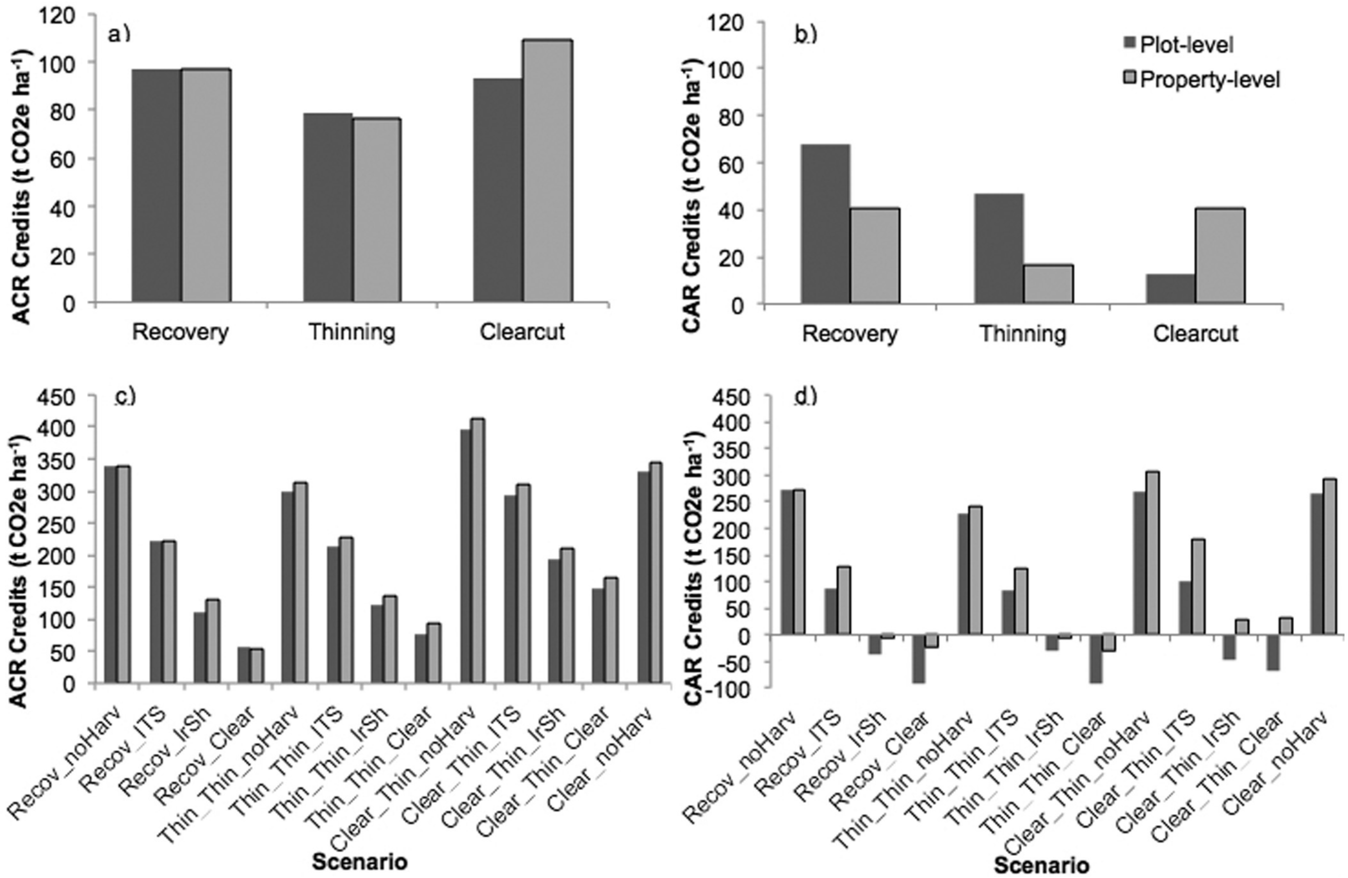
One advantage of CAR is that the protocol has been adopted by California's regulatory cap and trade program with slight modifications (Air Resources Board 2010). This could provide an additional market for CAR credits, as well as higher prices. With regulatory price assumptions starting at \$11·t CO_2e^{-1} in 2012 and rising to a high of \$50·t CO_2e^{-1} after 2020, two management scenarios generate positive NPV from the sale of offset credits alone: Recov_ITS at \$123 ± \$99·ha^{-1} and Recov_noHarv at \$256 ± \$100·ha^{-1}. When timber revenue is included, total NPV increases to \$147 ± \$100·ha^{-1} for Recov_ITS, whereas Recov_noHarv remains at \$256 ± \$100·ha^{-1} as no harvesting occurs (Fig. 7*c*). Total NPV values for these scenarios under CAR are comparable to the total NPV values under ACR at the higher voluntary market prices (Fig. 7*b*). They are also comparable to the timber-only NPV of more intensive management scenarios that are not eligible to generate offsets, although the uncertainty of the CAR estimates is much higher (Fig. 7).

4. Discussion

4.1. Rehabilitation success

Landowners have many reasons for owning and managing forestland, including aesthetics, recreation, enjoyment of wildlife, harvestable resources, and others (Butler et al. 2007). For this study, we assume that rehabilitation is a desired outcome. Stand structural metrics are often used to assess the success of restoration efforts because they influence key ecological functions and processes (McElhinny et al. 2005). Structural characteristics typical of mature forests such as multi-layered canopies, large tree sizes, and high biomass volumes have been associated with a

Fig. 6. Comparison of plot-level versus property-level carbon credit calculations after (*a*) 40 years under ACR, (*b*) 40 years under CAR, (*c*) 100 years under ACR, and (*d*) 100 years under CAR.



range of ecological functions, including bird abundance (DeGraaf et al. 1998), salamander abundance (McKenny et al. 2006), riparian habitat (Keeton et al. 2007), and carbon storage (Luyssaert et al. 2008). For this study, we use QMD, sawlog volume, and carbon storage as key metrics by which to measure the effectiveness of rehabilitation efforts. These structural metrics reflect tree size and density but do not account for tree form and quality, which are important considerations when rehabilitating high-graded stands. FVS does not have a built-in mechanism for altering these tree characteristics and assumes that all regenerated trees are of good form and acceptable growing stock. As a result, the financial viability of timber harvests, particularly sawlog harvests, may be overestimated.

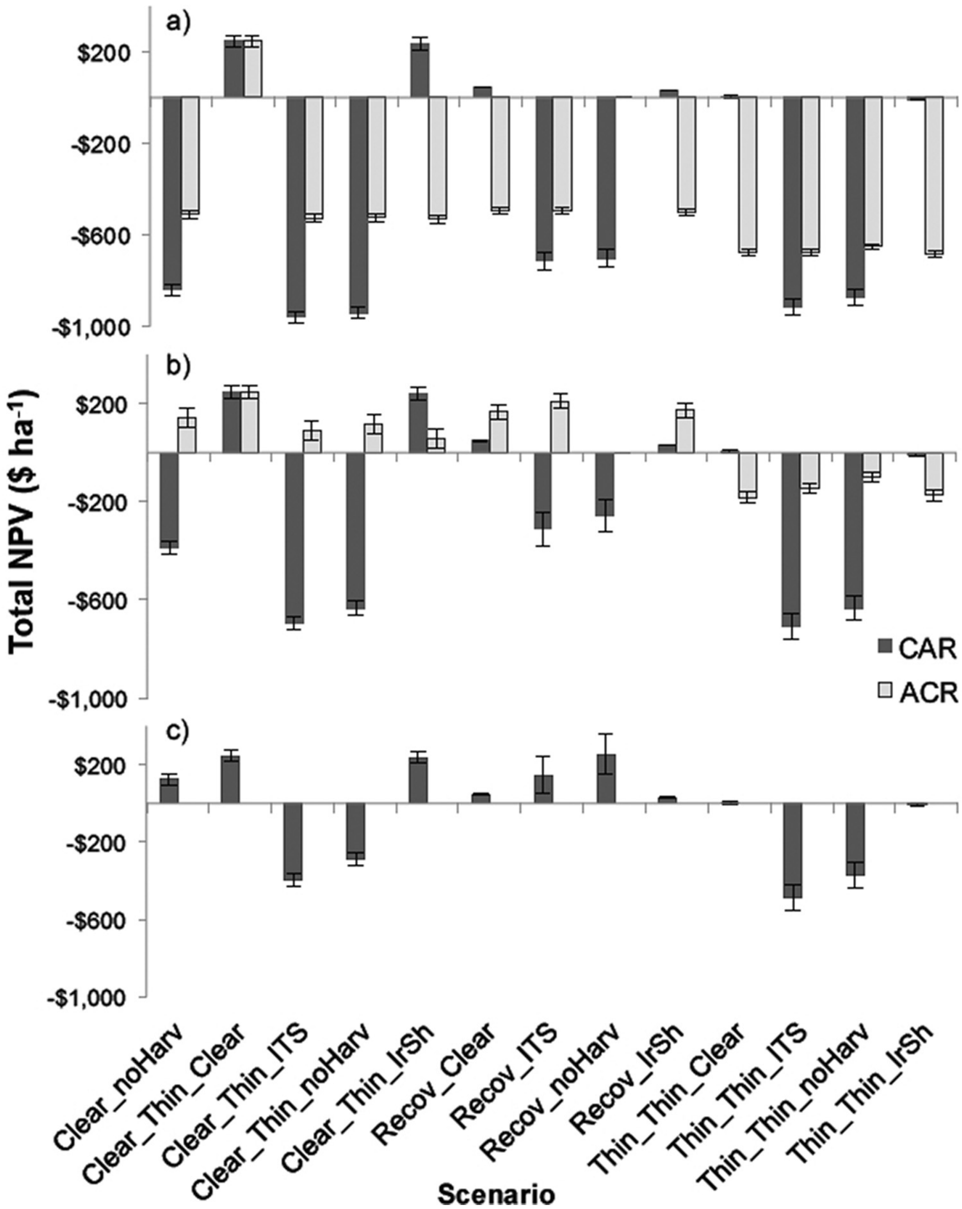
For a heavily harvested, poorly stocked forest, management scenarios with a long-term strategy of either no harvesting or low-intensity harvesting are most effective at improving stand structure and increasing carbon storage. This finding is consistent with previous research (Harmon and Marks 2002; Nunery and Keeton 2010). Studies have documented the natural ability of northeastern forests to recover from a range of disturbances without the need for human intervention (e.g., Foster and Orwig 2006). Our results show that an initial period of recovery is consistently one of the best options for improving stand structure, enhancing carbon storage, and generating carbon credits. It is also one of the lowest risk options for rehabilitating degraded forests because it does not require up-front investment. Scenarios that include initial recovery also generate high NPV from offsets because they avoid an initial decline in carbon stores and thus generate credits more quickly than other scenarios.

Our results also indicate that short-term rehabilitation activities across a range of intensities can also facilitate rehabilitation goals, as long as they are combined with low-intensity management as a long-term strategy. The most intensive rehabilitation treatment — an initial silvicultural clearcut to remove residual trees and regenerate a new cohort — can be an effective rehabilitation option, depending on subsequent management decisions. When combined with a long-term strategy of ITS or no harvest, this treatment can eventually regenerate poorly stocked sites, improve forest structure, and increase carbon storage. An initial clearcut may be an attractive option to landowners because it generates immediate financial return and may also improve tree form and quality. However, the overall success of this treatment depends on having adequate seed sources, successful regeneration, and vigorous regrowth — factors that are highly site-specific.

Clearcuts in the northeastern US have been associated with negative impacts such as runoff (Hornbeck et al. 1993), sedimentation (Binkley and Brown 1993), and nutrient leaching (Dahlgren and Driscoll 1994). Soil disturbance has also been shown to sometimes reduce soil carbon, depending on site characteristics, an effect that can persist for many years before recovering (Nave et al. 2010). Because CAR and ACR do not require accounting of soil carbon, it is possible that the benefits of clearcutting could be exaggerated (Buchholz et al. 2013). Alternatively, a degraded property such as Victory may already have depleted soil carbon due poor harvesting practices and extensive soil erosion in its past. Due to these uncertainties, we suggest that rehabilitation clearcuts be applied with caution, limited in scale, and targeted to areas with the poorest residual stocking.

Targeted thinning is another rehabilitation option that improves stand structure over time in our study. Stand improvement treatments, including crop tree release, were recently implemented in a study on the Penobscot Experimental Forest in Maine.

Fig. 7. The total net present value (NPV; discounted at a 5% annual rate) of selling wood products and carbon offset credits. Offset credits are considered under three price assumptions: (*a*) low prices within the voluntary market, (*b*) high prices within the voluntary market, and (*c*) high prices within the regulatory market specific to California's cap and trade program, in which only CAR-based offsets are currently eligible to participate.



Preliminary results indicate that treatments improve stand structure but are time-consuming and costly (L.S. Kenefic, unpublished). Similarly, our results show that thinning treatments generate lower financial return compared with other management options. Concerns have been expressed that FVS may underestimate the benefits of thinning (Saunders et al. 2008), although this concern may vary regionally. FVS is also unable to simulate a true, spatially explicit crop tree release. Thus, it is possible that targeted thinning treatments could achieve more substantial improvements than demonstrated in this study, despite up-front costs.

4.2. Role of carbon markets

This study supports the finding that carbon markets can provide additional incentives for sustainable forest management (Malmsheimer et al. 2008; Charnley et al. 2010). However, offset prices must be at least as high as those assumed under the higher voluntary market scenario for ACR ($10·t CO_2e^{-1} rising to $30·t CO_2e^{-1}) and the regulatory market scenario for CAR ($11·t CO_2e^{-1} rising to $50·t CO_2e^{-1}) to provide financial benefits. Otherwise, undertaking an offset project can come at a significant net cost.

The economic assumptions used in this study draw from some of the first US forest carbon projects, as well as the best available market predictions. A 5% annual discount rate was used to calculate NPV because this is the rate used to develop the baseline scenario for nonindustrial private forest (NIPF) owners under the ACR protocol. This rate falls between the 6% rate assigned to private industrial owners and the 4% rate assigned to nonfederal public landowners and nongovernmental organizations due to a consideration for both market and nonmarket benefits. Using alternative discount rates would substantially influence our results: a higher discount rate would reduce the NPV of our rehabilitation scenarios, whereas a lower discount rate would increase

NPV. At a 5% discount rate, total discounted costs for developing, monitoring, and verifying CAR and ACR projects in this study were \$1135·ha^{-1} and \$1198·ha^{-1}, respectively, supporting the finding that carbon projects are expensive to implement (Galik et al. 2009, 2012). In practice, the costs of developing a project are highly variable and must be considered on case-by-case basis. Early evidence suggests that larger properties, and aggregations of smaller properties, have lower average costs per hectare through economies of scale (Galik et al. 2009). However, we were conservative in our assumptions to avoid overstating the potential benefits from carbon projects. If these costs were to decline, or if offset prices were to increase substantially, carbon markets could become even more appealing as a complement to traditional forest management.

4.3. Importance of accounting

Like previous studies, this study found that accounting methods greatly influence carbon outcomes (Pearson et al. 2008; Foley et al. 2009). While the ACR and CAR protocols are similar in their basic framework, specific accounting requirements vary substantially (Tables 3 and 6). An unexpected finding of this study is that carbon credit calculations at the plot level differ from those at the property level.

Under CAR, the highly variable Victory property contains some plots with higher carbon stores than the baseline, which allows those plots to generate carbon credits immediately in absence of initial harvest. An initial thinning may reduce carbon slightly, but an initial clearcut will reduce carbon substantially on these plots, causing a reversal, which then has to be compensated. Because this only affects the plots with relatively high carbon stores, the many plots that have low carbon stores will remain unaffected, causing a high degree of variability in the plot-level data. However, averaged across the property, carbon stores start out below the baseline, generating no immediate credits, but causing no initial reversal from the clearcut. Thus, when calculations are made at the property level, the clearcut scenario generates credits more quickly (because there is no initial payback period), making it similar to the recovery scenario after just 40 years (Fig. 6*b*).

This accounting discrepancy is more pronounced under CAR than ACR, because CAR's baseline is a 100-year average. Baseline carbon can thus start at a different point than project carbon, producing an initial disparity at the beginning of the project. This disparity can yield a flush of credits if the project starts above the baseline, as has been documented for certain well-stocked properties (Yonavjak et al. 2011). For overharvested, poorly stocked forests, this discrepancy can cause an initial debt that must be repaid. ACR's baseline, in contrast, starts from the same point as the project activity and does not create the same initial disparity.

These findings indicate that carbon credit results depend substantially on how the calculations are performed. Calculating credits at the plot level may be more accurate because it allows for an estimation of uncertainty and reflects the underlying variability of the forest (Ray et al. 2009). However, property-level calculations are generally more straightforward and easy to interpret. Trade-offs such as these have emerged as a key issue in offset program design — balancing the need to make protocols easy enough to use, while rigorous enough to withstand scrutiny. The CAR protocol was adopted for use in California's regulatory program because of its perceived technical rigor and credibility (Air Resources Board 2010).

4.4. Uncertainties and limitations

As with any modeling study, many assumptions influenced our findings. FVS has been calibrated with empirical data for different regions of the US and validated in multiple field tests (Fahey et al. 2010). However, FVS has also been criticized for applying the same equations across large regions of the country (Ray et al. 2009) and occasionally producing modeled results that differ from observed patterns (Saunders et al. 2008). It can also be cumbersome within FVS to stagger silvicultural treatments spatially and temporally. Rather than tailor each of the 13 rehabilitation scenarios to the unique conditions of our site's 155 plots, we applied the scenarios to all plots simultaneously, based on the average condition of the property as a whole. This produced relatively large carbon fluctuations for more intensive management scenarios and may not be a realistic reflection of how a forester would manage such a spatially heterogeneous property.

While there are notable disadvantages to using models to predict forest dynamics, they provide one of the only ways to understand how these dynamics might play out across large areas and long periods of time (Gratzer et al. 2004; Kurz et al. 2009). Our results represent a range of possible future conditions and elucidate the main differences between broad categories of management. Thus, the results have relevance for overharvested and high-graded forests across temperate North America (Fajvan et al. 2002) and possibly other regions globally that have a history of high-grading (Bravo and Montero 2003).

5. Conclusion

This study is among the first to investigate the specific opportunities and challenges of using carbon markets to rehabilitate high-graded forests. While more research is needed across different forest types and conditions, our findings have immediate implication for thousands of hectares of understocked timberland across the northeastern US (Hoover and Heath 2011).

Rehabilitation can generate positive NPV from carbon offsets when the activity involves a long-term strategy of low intensity or no management. If carbon market prices are high enough, offsets can provide a new stream of revenue to complement traditional timber harvests. If carbon market prices are not high enough, timber harvests will continue to provide a greater source of NPV, particularly from more intensive forest management. Not all landowners will be comfortable with the uncertainty inherent in new markets. All landowners will need to assess whether carbon market participation is compatible with other management objectives. However, an increasing number of conservation-minded landowners may be motivated by a style of management that combines traditional forest products with new ecosystem services.

Legitimate concern has been expressed that using carbon markets to promote ecological restoration may result in generating offset as quickly and cheaply as possible, rather than on achieving restoration goals (Galatowitsch 2009). However, many elements of carbon offset accounting such as long-term monitoring and third-party verification may also support restoration outcomes. In addition to storing carbon, restoration can increase forest productivity, improve economic value, and enhance ecological function (Stanturf and Madsen 2005; Galatowitsch 2009). To overcome the compounded challenges facing high-graded forests of poor stocking, low value, and high up-front costs, it may be necessary to combine multiple sources of incentives, including carbon markets.

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