

EFFECTS OF IMPROVED FOREST MANAGEMENT AND LOBLOLLY PINE GENOTYPES ON CARBON SEQUESTRATION AND PROFITABILITY IN THE SOUTHEASTERN UNITED STATES

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ABSTRACT. Since 1880, the average global temperature has risen by more than 1°C (National Aeronautics and Space Administration, 2021). Global climate change remains at the center of today’s environmental debates and continues to impact global ecosystems. To prevent global climate change from reaching an irreversible level, scientific studies developed solutions that would decelerate the rise of CO₂ concentration in the atmosphere, adapt natural or human systems, and raise societal awareness. Forests, which are an important natural carbon sink, are considered as one of the potential solutions addressing global climate change. This study evaluated the profitability of joint timber-carbon production and estimated the value of carbon sequestration with improved forest management and improved loblolly pine (*Pinus taeda* L.) genotypes in the southeastern U.S. using the American Carbon Registry’s methodology. It was observed that joint timber-carbon production could generate a larger profit than traditional timber-only production, benefiting the environment and forest landowners.

Keywords: *Pinus taeda*; carbon offset; American Carbon Registry; joint timber-carbon production.

1 INTRODUCTION

Global climate change is defined as the long-term alteration of average global temperatures and typical weather patterns (Field et al., 2012). It is considered as one of the greatest environmental challenges of the present time and it is at the center of environmental policy debates. Extreme weather events and natural disasters such as wildfires, floods, droughts, storms, changes in seasonal patterns and rainfall distribution, rising temperatures, the melting of glaciers and polar icecaps, and rising sea levels are often perceived as the most apparent consequences of climate change (Field et al., 2012). Research indicates that supply chains tied to agriculture or maritime trade will be disproportionately affected by the results of climate change (Hsiang et al., 2017). Another challenge is feeding the world’s growing population. If the current trends of increasing atmospheric carbon levels continue, by the end of the century global temperatures may possibly rise by 1.3–1.9 °C above pre-industrial levels, and by 2050, an additional 290 mil-

lion people could suffer malnutrition (Smith and Myers, 2018).

Climate mitigation and adaptation strategies are important tools for addressing climate change and its impacts. These strategies are aimed at reducing carbon emissions and are reflected in individual countries’ domestic policies as well as in international initiatives, such as the Paris Agreement of 2015 and the following UN climate change conferences, including the latest COP 30 in Belem in 2025.

Expanding carbon sinks to decrease the CO₂ concentration in the atmosphere is the main purpose of greenhouse gas mitigation. Forest-based carbon mitigation strategies are a very potent tool, while providing a range of co-benefits. Beyond the regulation of the natural carbon cycle, forest-based mitigation contributes to regulating temperature and precipitation by impacting soil and hydrological cycles (Anderson-Teixeira and Belair, 2022). According to the U.S. Environmental Protection Agency (EPA, 2024), land-use, land-use change, and forestry (LULUCF) activities stored 810.7 million met-

ric tons of CO₂ (MtCO₂) in 2022, an amount sufficient to offset 13.6% of the total 2022 emissions in the U.S. This indicates that forests can play a significant role in reducing atmospheric CO₂ concentrations and help mitigate global warming and its effects.

The U.S. is one of the global leaders in forest products manufacturing and trade. The most important U.S. region for forestry activities is the southeastern U.S. (Prestemon et al., 2015). This region comprises 32% of the nation's forests and is the largest timber-producing region in the country, providing 60% of the nation's timber production (Howard and Jones, 2016; Oswalt and Smith, 2014). In addition, the forest products industry in the U.S. generates approximately 4% of the nation's total manufacturing-related gross domestic product (American Forest and Paper Association, 2020).

Loblolly pine (*Pinus taeda* L.) is the most important tree species for industrial wood production and forest markets in the southeastern U.S. Pine plantations cover an area of about 40 million acres in the region, and loblolly pine plantations have the largest acreage compared with other pine species (Zhao et al., 2019; Oswalt et al., 2019). Due to advanced tree breeding research efforts over the past 50 years, the productivity of pine plantations has tripled (Fox et al., 2007; Jokela et al., 2010). Therefore, loblolly pine could be one of the most important species for carbon sequestration efforts due to its rapid growth. It is estimated that loblolly pine plantations in Georgia capture 1–4 MtCO₂ per acre (0.4047 ha) per year (Rousseau, 2008).

Fast growth combined with improved forest management (IFM) could increase the carbon storage capacity of the existing forests. IFM projects are the most widely used forest project type in the cap-and-trade program operated by the California Air Resources Board (Parajuli et al., 2021). Yin and Sedjo (2001) suggested that improved forest management projects can increase carbon storage benefits while improving the economic performance of forest management. Consequently, with improved forest management approaches, forest landowners can develop and manage more profitable plantations while increasing carbon storage.

With the emergence and increases in the demand for carbon offsets in the past years, a market has formed where various private and government organizations verify, monitor, credit, and trade carbon offsets. According to the Ecosystem Marketplace (EM) report (2021), the total global cumulative voluntary carbon market (VCM) value was \$6.7 billion in the first eight months of 2021. Moreover, it reported \$748 million of voluntary carbon market transactions over the same period. Carbon credit prices are predicted to rise in the future. An increase by a factor of 15 or more may occur by the end of the decade, and an increase by a factor of up to 100 by

2050 could be expected for carbon credit prices according to the Taskforce on Scaling Voluntary Carbon Markets (TSVCM), funded by the Institute of International Finance (IIF) (Blaufelder et al., 2021).

For carbon sequestration to be effective, government or voluntary organizations' policies must encourage carbon sequestration that is additional to the normal business operation (Meyers, 1999; Woodhams et al., 2012). The Kyoto Protocol raised important questions about permanence, leakage, and additionality (Karsenty et al., 2003) also for forest carbon projects. Consequently, to ensure both global and individual project success and profitability in carbon trade, carbon sequestration must be additional to what would have been business as usual, any leakage should be properly accounted for, and carbon should be stored permanently.

In the carbon market, various organizations act as carbon registries, conducting carbon credit transactions and providing methodologies that address additionality, leakage, and permanence considerations. Carbon crediting registries are an important component of the market that helps create a credible, fungible offset commodity. They track carbon projects and issue offset credits for each unit of emission reductions that is verified and certified. The American Carbon Registry (ACR), for example, is a non-profit organization that has developed a methodology for measuring, reporting, capturing, storing, and verifying greenhouse gas emission reductions.

There is a scarcity of published studies that assess the economic and environmental effects of improved pine genotypes as well as studies focused on joint timber-carbon production. The primary goal of this study is to evaluate the profitability of joint timber-carbon production and estimate the value of carbon sequestration with improved forest management (IFM) founded on genetic gain in growth of loblolly pine seedlings in the southeastern U.S. Four loblolly pine genotypes developed by ArborGen Inc. were used for analysis. Their growth and yield were simulated for 50 years. This information was used to assess the American Carbon Registry pathway to evaluate sequestered carbon and profitability of joint timber-carbon production. Furthermore, this research aims to compare landowners' joint timber-carbon production options and discuss the environmental value of carbon sequestration through forests.

2 MATERIALS AND METHODS

2.1 Loblolly pine genotypes

This assessment relies on four improved loblolly pine genotypes developed by ArborGen Inc. These genotypes include OP-C (Open Pollinated Control), OP-A (Open Pollinated Average), CMP-A (Control Mass Pollinated

Average), and Variety. The Tree Improvement Cooperative of North Carolina State University validated the genetic gain of genotype categories' data.

For this study, the data set was generated by The Simulator for Intensively Managed Stand (SiMS) (Forest Tech International, 2003) that uses the PMRC (Plantation Management Research Cooperative) equation system combined with the genetic gain information. SiMS models both the whole plantation and individual trees in a hybrid manner. It is a diameter distribution projection model that can simulate intensive forest management and classify products (pulpwood [PW], chip and saw [CNS], sawtimber [ST], poles, etc.) according to the minimum top diameter outside the bark and the minimum merchantable DBH (diameter at breast height) class (Henderson et al., 2013).

In this study, the OP-C genotype represents the business-as-usual baseline, reflecting conventional open pollinated planting material under standard management conditions in the southeastern U.S. Baseline carbon stocks were modeled on a year-by-year basis using the same growth and yield framework applied to all improved genotype scenarios. This approach ensures that baseline conditions change over time rather than being treated as a static reference. Additional carbon sequestration is therefore defined as the annual difference in carbon stocks between each improved genotype and the OP-C baseline, allowing additionality to be evaluated consistently throughout the rotation period. Additionality arises from genetically improved planting material, which increases growth rates and standing biomass relative to the OP-C baseline under the same management conditions.

All seedling studies in the data set were conducted in the Lower Coastal Plain of the southeastern U.S. on a non-spodosol soil type in a 1-acre area. The stand was formed by planting and was established on bare land. The dataset used contained 50-year projections of stands with growth and yield information for four different genotypes (Appendix, Table A.1). Starting from age zero, the growth patterns of each genotype can be followed until age 50. To monitor the development of each genotype, annual height, trees per acre, basal area per acre, quadratic mean diameter, and total yield information were projected as outputs of SiMS. Additionally, yield information by product class, diameter class, and year were projected. A stand development report containing DBH class, average height, and volume per acre information was prepared before and after the thinning process.

For timber costs and benefits, yield information by product classes was generated by SiMS, and 3rd quarter 2021 TimberMart-South prices were used to determine economic benefits (TimberMart-South, 2021). To

calculate costs and benefits of carbon trade, ACR Standard Version 7.0 was followed (American Carbon Registry, 2020). The discount rate was 6% for all calculations to comply with ACR IFM project requirements (American Carbon Registry, 2018). Survey data for silvicultural practices such as chemical and mechanical site preparation, planting, fertilization, mid-rotation release, and herbaceous weed control were taken from Maggard (2021) and were used to determine management costs (Table 1). Hunting leases and property taxes were assumed to offset each other. It should be noted that all yield values were presented in short tons (1 short ton = 2,000 pounds or 907.18 kg) and all carbon values were presented in metric tons (MtCO₂) throughout this study.

2.2 Calculations of NPV and LEV

With 50 years of growth and yield tables of four genotypes, first, the optimum economic rotation period was determined for each genotype using the land expectation value (LEV) criterion. For this, net present value (NPV), which is used to examine the profitability of future projects (in this instance a single rotation), was determined to calculate the difference between the present values of future cash inflows and cash outflows. LEV measures the net present value of forestland use in perpetuity considering incomes, costs, and interest rate (Faustmann, 1849). It predicts the present value of the net returns from the perpetual series of clear-cut and replanting (Susaeta and Demers, 2019).

To determine optimum economic rotation period, the following equations were used:

$$NPV = \sum_{t=0}^n \frac{R_t}{(1+i)^t} - \sum_{t=0}^n \frac{C_t}{(1+i)^t} \quad , \quad (1)$$

$$LEV = NPV \frac{(1+i)^t}{(1+i)^t - 1} \quad , \quad (2)$$

where:

- R_t is the revenue in year t ;
- C_t is the cost in year t ;
- i is the discount rate; and
- t is the number of periods.

For calculating carbon sequestration benefits, the outside bark (OB) green ton values for each genotype were used. To calculate belowground weight, crown weight, bark weight, and total MtCO₂ (Alabama Forestry Com-

Table 1 Management and seedling costs (\$/acre).

Activity	Year	OP-C (605)	OP-A (605)	CMP-A (605)	Variety (558)
Mechanical site prep.	0	131	131	131	131
Chemical site prep.	0	82	82	82	82
Seedlings	0	31	44	117	195
Differential in seedling cost	0	0	13	86	164
Planting	0	85	85	85	85
Herbaceous weed control	0	53	53	53	53
Mid-rotation release	15	72	72	72	72
Fertilization (DAP+urea)	16	87	87	87	87

Adapted from “Costs & Trends for Southern Forestry Practices,” A. Maggard, 2021; “2019/2020 ArborGen Product Catalog,” 2019/2020, ArborGen Inc. *Note:* Annual hunting lease and annual property taxes are not included because they are assumed to offset each other. TPA in parentheses: trees per acre. OP-Control, OP-Average, and CMP-Average have an 85%, and Variety a 92%, survival rate.

mission, 2009; Cairns et al., 1997; Chojnacky et al., 2014), the following equations were used:

$$\text{Total tree weight} = 1.12 \times \text{bole weight} \quad , \quad (3)$$

where:

- 1.12 is the total tree factor.

$$\begin{aligned} \text{Below ground weight} &= 0.15 \\ &\times \text{above ground weight} \quad , \end{aligned} \quad (4)$$

where:

- 0.15 is the average root ratio.

$$\begin{aligned} \text{Total MtCO}_2 &= \text{Total merchantable weight} \times 0.47 \\ &\times 0.50 \times 3.67 \times 0.9072 \times 0.982 \quad , \end{aligned} \quad (5)$$

where:

- 0.47 is the specific gravity;
- 0.50 is the ratio of sequestered carbon in timber;
- 3.67 is the carbon to carbon dioxide equivalent;
- 0.9072 is the short tons to metric tons equivalent; and
- 0.982 is the outside bark weight to inside bark weight equivalent.

The equations used to estimate biomass components are based on established allometric relationships, while the conversion of biomass to carbon to CO₂ relies on standard conversion constants summarized in Appendix Table A.2.

Further, calculated MtCO₂ values for each genotype were used to compute costs and benefits following the ACR’s methodology and requirements to determine the

benefits and costs of carbon production. Detailed information about costs and benefits calculations can be found in the following Section 2.3.

Lastly, the equivalent annual annuity (EAA) flow was calculated to make even comparisons between genotypes using the following equation:

$$\text{EAA} = \text{NPV} \frac{i}{1 - (1 + i)^{-t}} \quad , \quad (6)$$

where:

- EAA is the equivalent annual annuity;
- NPV is the net present value;
- i is the discount rate; and
- t is the time.

2.3 Carbon Project Development Scenario

For each genotype, one-acre stands managed for 44 years with two rotations were evaluated. According to ACR’s methodology, OP-C was selected as the baseline (business as usual). A thinning age of 14 was selected, and for comparative purposes, an optimum economic rotation age of 22 was used for all genotypes. The same rotation period was used to facilitate the comparison between genotypes (Figure 1 and Table 2). A cost and benefit table for each improved genotype was created to compare the profitability of joint timber-carbon production (Appendix, Table A.3).

For the costs and benefits analysis of these three genotypes, their cost differs based on the seedling prices. However, the benefit from each genotype is examined from three different aspects: yield, product classes at thinning (PW, CNS), and product classes at the clear-cut (PW, CNS, ST, Poles). Higher yield and wood quality are expected to provide higher income from thinning,

Table 2 Yield information of four loblolly pine genotypes (ton/acre) and genetic gain ratio.

Genotype	Thinning yield	Final harvest yield	Total yield	Pulpwood	Chip and saw	Sawtimber	Poles	Genetic gain at age 6
OP-Control	58.9	118.3	177.2	106.7	50.6	15.9	4.0	40%
OP-Average	69.5	125.9	185.4	116.7	46.9	25.4	6.4	55%
CMP-Average	79.4	135.4	214.8	104.8	60.9	39.8	9.6	72%
Variety	87.9	142.9	230.8	85.2	78.1	53.9	13.5	85%

Adapted from “Tree Lines,” M. Cunningham, 2021, ArborGen Inc. Genetic gain: growth gain at age six over unimproved seedlings. (<https://www.arborgen.com/treelines-february-2021-1st-edition>)

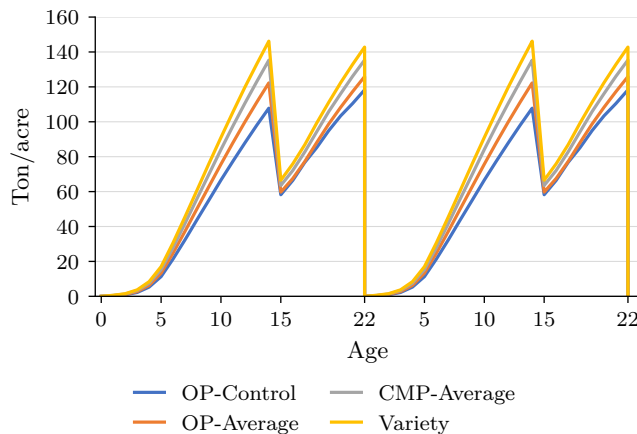


Figure 1 Growth and yield comparison of four loblolly pine genotypes. Note: thinning applied at age 14 (see data in Supplement 3).

clear-cut, carbon sequestration, and long-life products to landowners in this project.

2.3.1 Costs

Mechanical and chemical site preparation, fertilization, and thinning should be applied for each genotype to maximize wood volume growth. Even though using improved genotypes has been associated with higher cost of seedlings, the cost for the regeneration and intensive management is expected to be the same as for the OP-C loblolly pine genotype. To calculate the cost for one acre of loblolly pine plantation, seedling costs were calculated for each genotype. ACR fees, management, and seedling costs were considered (Tables 1 and 3). Fixed ACR project fees are reported on a one-acre basis to enable direct comparisons with per-acre timber and carbon revenues. This scaling approach is applied solely as a normalization method for stand-level economic evaluation and does not imply that actual project costs increase linearly with project area. In practice, fixed ACR-related costs would be distributed across larger project areas, resulting in lower per-acre costs as project size increases. Accordingly, expressing these fees on a one-acre

basis provides a conservative cost estimate within the economic analysis.

Table 3 American Carbon Registry fee schedule (\$).

Fee item	Amount
Account opening fee (Project, Transaction, Corporate)	500.00
Annual account fee (Project, Transaction, Corporate)	500.00
Project eligibility screening (ACR methodologies)	1,000.00
ACR verifier application fee	2,000.00
Issuance fee (per offset)	Free
Activation fee (per offset)	0.15
Transaction fee (per offset)	0.02

Adapted from “ACR fee schedule,” n.d., American Carbon Registry. (<http://americancarbonregistry.org/how-it-works/membership/acr-fee-schedule.pdf>)

2.3.2 Benefits

The main difference in benefits for these four genotypes is based on gain in volume and quality of product classes. The 2021 ACR average price of per MtCO₂ for forestry and land use was \$11.37 (Ecosystem Marketplace, 2021), and average prices for timber products in the Lower Coastal Plain market were \$12.30, \$20.18, \$29.08, and \$42.62 (per ton) for PW, CNS, ST, and Poles, respectively (TimberMart-South, Q3, 2021). Prices were the average of TimberMart-South region 2 (coastal) in the following southern states: South Carolina, North Carolina, Georgia, Alabama, Florida, Mississippi, Louisiana, and Texas. To compare costs and benefits, the total profit from two rotations was calculated by subtracting present values of total cost from total benefit.

The scenario is summarized as follows:

- Carbon Registry: ACR;
- Project Developer: Forest Carbon Inc.;
- Methodology: ACR methodology compliance with improved forest management (IFM) requirements;

- Genotypes of loblolly pine: OP-Control (Baseline), OP-Average, CMP-Average, Variety;
- Rotation length: 22-year;
- Thinning age: 14th year;
- Carbon credit contract period: 44 years;
- Risk Assumption: no land sales or catastrophic events occur during the project period;
- ACR minimum fixed fees for 40 years: \$23,500;
- ACR fees/MtCO₂: \$0.17.

The equation below describes the process of determining additional annual net greenhouse gas emission reductions and Emission Reduction Tons (ERTs) issued for a period for which a valid verification report has been filed with ACR. According to ACR IFM methodology (2018), the following equation was used:

$$ERT_t = C_{ACR,t} = (\Delta C_{P,t} - \Delta C_{BSL,t}) \times (1 - LK)(1 - UNC_t)(1 - BUF) \quad , \quad (7)$$

where:

- ERT_t is the Emission Reduction Tons (in MtCO₂) issued with vintage year t , v7.0;
- $C_{ACR,t}$ is the annual net greenhouse gas emission reductions (in MtCO₂) at time t ;
- $\Delta C_{P,t}$ is the change in the project carbon stock and GHG emissions (in MtCO₂) for year t ;
- $\Delta C_{BSL,t}$ is the change in the baseline carbon stock and GHG emissions (in MtCO₂) for year t ;
- LK is the leakage discount;
- UNC_t is the total project uncertainty (in %) for year t . UNC_t will be set to zero if the project meets ACR's precision requirement of within $\pm 10\%$ of the mean with 90% confidence. If the project does not meet this precision target, UNC_t should be the half-width of the confidence interval of calculated net GHG emission reductions; and
- BUF is the non-permanence buffer deduction as calculated. BUF will be set to zero if an ACR-approved insurance product is used. The BUF value is taken from the ACR Tool for Risk Analysis and Buffer Determination (15%).

3 RESULTS

Figure 2 presents the LEV for the four genotypes. As can be seen, the optimum economic rotation time ranges between 21–23 years. For this study, 22 years were selected for all genotypes. Better genotypes can provide

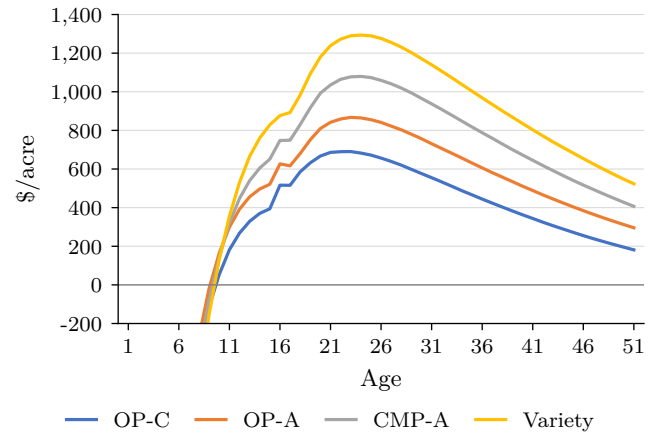


Figure 2 Land expectation value. Note: thinning was conducted at age 14 (see data in Supplement 3).

shorter rotation times with higher income, as follows: OP-C < OP-A < CMP-A < Variety.

To illustrate the profitability of joint timber-carbon production, first, management, seedling, and offset registration costs were calculated (Table 4). It is shown that the cost difference relies upon the price/quality of the genotype and intensity of the site preparation as well as the amount of creditable carbon offsets.

Second, timber revenue generated from the stand was calculated using stumpage prices for both thinning and clear-cut harvests in terms of PW, CNS, ST, and Poles volumes for each genotype (Table 5). Higher quality genotypes generate higher timber revenue in both thinning and clear-cut.

Third, crown weight was calculated following Equation 3 and root weight was calculated following Equation 4. After adding these values up, total tree weight was calculated above and below ground. Following Equation 5, the bark weight and water content were extracted, short tons were converted to metric tons, carbon amount in timber was calculated, and carbon was converted to CO₂. In conclusion, total MtCO₂ for every genotype for an acre at age 22 were determined (Table 6).

These MtCO₂ values were used to calculate carbon offsets through ACR requirements. ACR Standard v7.0 (2020) and ACR Improved Forest Management Methodology v1.3 (2018) were followed to examine costs and benefits of joint timber-carbon production for landowners. To estimate profit generated from joint timber-carbon production through ACR IFM methodology (Equation 7), the total ERT were calculated over the baseline (OP-C) for all project genotypes (Table 6). It should be noted that ACR also considers sequestered carbon in HWP along with carbon offsets generated from standing trees (HWP values are included in the total

Table 4 Management, seedling (\$/acre), and offset registration costs (\$).

Cost type	Year	OP-C	OP-A	CMP-A	Variety
Seedling and site prep.	0	382.00	395.00	468.00	546.00
Mid-rotation release	15	72.00	72.00	72.00	72.00
Fertilization	16	87.00	87.00	87.00	87.00
ACR opening fee	1	4,000.00	4,000.00	4,000.00	4,000.00
Annual fee ^a	—	500.00	500.00	500.00	500.00
Fee per offset ^b	—	0.17	0.17	0.17	0.17

Note: ^a Annual fee from year 1 to year 40; ^b Fee charged for every MtCO₂ once credited.

Table 5 Timber revenues (\$/acre).

Year	OP-C	OP-A	CMP-A	Variety
14	740	876	1,081	1,331
22	2,379	2,712	2,999	3,436

Table 6 Sequestered MtCO₂ and generated offsets (per acre).

	OP-A	CMP-A	Variety
Sequestered MtCO ₂	124.6	134.0	141.3
HWP offsets	42.4	47.4	51.7
Total offsets (ERT)	284.7	297.4	307.7

HWP = Harvested Wood Products, ERT = Emission Reduction Tons.

ERT values). Then, multiplying the total ERT values by the 2021 ACR average carbon offset price (\$11.3), carbon revenue was calculated (Table 7).

Furthermore, the volume of harvested timber (ton/acre) from thinning (OP-A: 139.0, CMP-A: 158.8, Variety: 175.8) and from clear-cuts (OP-A: 251.8, CMP-A: 270.8, Variety: 285.6) was calculated for the entire project term (Figure 3).

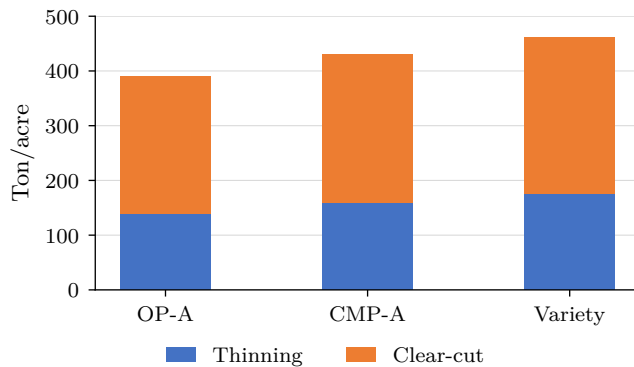


Figure 3 Harvested timber volume from thinning and clear-cut of project genotypes. Note: this figure represents two 22-year rotation periods (see data in Supplement 3).

Next, with ACR fees in addition to management and seedling costs, costs-benefits and cashflow tables were created for each project genotype (Appendix, Tables A.4a, A.4b, A.4c, A.4d). Then, present values of costs and benefits to determine the profitability of this joint timber-carbon production approach were found (Table 7).

To specify profitability of the joint timber-carbon approach and compare yearly income levels of genotypes on a one-acre basis, EAA values were calculated (Equation 6 and Table 8).

After all profitability calculations of the joint timber-carbon approach were conducted for current pricing patterns, sensitivity analysis was conducted to predict LEV linked to different offset prices (Table 9).

Finally, cost-effectiveness calculations were conducted for another scenario which contains no clear-cut or thinning during the 44-year project period under the same methodology to observe the difference between joint timber-carbon production and only-carbon production (Table 10). To see what level of MtCO₂ pricing would be enough to reduce the EAA difference between these two approaches to zero, a break-even point was calculated, requiring MtCO₂ prices to be around \$66.

4 DISCUSSION

There is an expectation that in the coming decades, the effects of climate change will become more pronounced in many regions (National Aeronautics and Space Administration, 2021). When global warming reaches 2 °C, extreme heat will more often reach vital tolerance thresholds for agriculture and health (Pörtner et al., 2022). As many studies on this topic suggest, forests can play an effective role in slowing down global warming through increased carbon sequestration as they function as natural carbon sinks (Griscom et al., 2017). Carbon sequestration can be an important source of income for forest landowners while generating environmental benefits. Above- and below-ground biomass, litter layer, and soil in forests are considered as carbon sinks. In addition

Table 7 Joint timber-carbon production project present values (\$/acre).

	Mgmt. & seed. costs	ACR fees	Timber sale rev.	Carbon sale rev.	Total rev.	Total cost	Total
OP-A	587	121	1,387	1,175	2,563	708	1,855
CMP-A	680	122	1,674	1,243	2,918	802	2,116
Variety	780	123	1,970	1,306	3,276	903	2,373

Table 8 EAA (\$/acre).

	OP-A	CMP-A	Variety
Total cost	46.10	52.30	58.80
Total revenue	166.60	189.70	213.00
Net EAA	120.50	137.40	154.20

Table 9 Sensitivity analysis of LEV in terms of carbon offset pricing.

MtCO ₂ Price (\$)	OP-A (\$/acre)	CMP-A (\$/acre)	Variety (\$/acre)
0.00	734.00	943.00	1,155.00
4.00	1,182.00	1,417.00	1,652.00
8.00	1,631.00	1,891.00	2,150.00
11.37	2,008.00	2,290.00	2,570.00
16.00	2,527.00	2,839.00	3,146.00
20.00	2,975.00	3,313.00	3,644.00
24.00	3,423.00	3,787.00	4,142.00
28.00	3,871.00	4,261.00	4,639.00
32.00	4,319.00	4,735.00	5,137.00
36.00	4,767.00	5,209.00	5,635.00
40.00	5,215.00	5,683.00	6,133.00

Note: \$11.37 is the ACR average carbon offset price in 2021 (Ecosystem Marketplace, 2021).

Table 10 Difference in EAA of joint timber-carbon and only-carbon projects (\$/acre).

	OP-A	CMP-A	Variety
Joint timber-carbon production	120.50	137.40	154.20
Only carbon production	85.20	95.40	101.40
Difference	35.26	42.07	52.74

to timber production, which is the biggest income source from forests, carbon sequestration has started to develop management and income alternatives for landowners with an increasing market volume.

In this study, the profitability of joint timber-carbon production was examined under present conditions for forest landowners. Following ACR IFM methodology, OP-C was selected as the baseline genotype, and the gen-

erated offsets were calculated throughout the project for each project genotype (ton/acre): OP-A: 284.7, CMP-A: 297.4, and Variety: 307.7. Furthermore, the amount of harvested timber (ton/acre) was calculated throughout the project for each project genotype: OP-A: 390.8, CMP-A: 429.6, Variety: 461.4. Using prices for carbon and timber, the net present revenue from joint timber-carbon production was calculated. Then, profitability was determined by subtracting management, seedling, and ACR costs for each genotype (Table 7). The profitability comparison in Table 7 suggested that joint timber-carbon production can be profitable and create new opportunities for landowners.

It is important to note that better genotypes involve higher seedling cost, but they also provide greater profits (Variety > CMP-A > OP-A). Additionally, sensitivity analysis was conducted on carbon offset pricing to predict future LEV of the joint timber-carbon approach in terms of increasing trends in prices (Table 9). Then, the break-even point was found around \$66.00 per carbon offset to equalize the EAA of joint timber-carbon production and only-carbon production (no thinning or clear-cut during the project term) under ACR's IFM methodology.

Ahtikoski et al. (2020) came to similar conclusions and suggested that both genetic gain and joint timber-carbon production can increase economic returns of a forest project. Looking ahead, increases in carbon prices might alter the way forests are managed in the future.

It should be noted that forests are well suited for carbon projects, and removals from one forest parcel can be covered/offset by other forest parcels in terms of carbon stocking levels. In this case, to be able to make meaningful comparisons, one-acre stands that are typical for forest economic analysis were considered. For that reason, in the ACR scenario, at the end of the first rotation period, a clear-cut was modeled. As a result, no carbon credit revenue is generated during the second rotation in our accounting results, because the clear-cut harvest at the end of the first rotation removes the accumulated aboveground carbon gains that produced positive ERTs during the first rotation. Under the applied carbon accounting framework, carbon sequestra-

tion occurring in the second rotation primarily rebuilds biomass stocks that were previously credited and subsequently harvested, resulting in an effectively zero net additionality over the second rotation. Harvested wood products are accounted for at the time of harvest and their economic value is realized through timber revenues; however, HWP-related carbon does not generate additional ERT sufficient to offset the post-harvest reset of standing carbon stocks. Consequently, economic returns in the second rotation are driven by timber revenues rather than carbon credit revenues. When the management scenario was changed to no clear-cut but just three thinnings in 44 years, a significant decrease was observed in timber revenue. Finally, in this study, carbon in dead trees, soil, foliage, and litter layer was not considered. Including these factors could increase profit generated from carbon trade through forests.

Forests provide many services other than timber production, and valuing these services provides different options to landowners. As a result, it was demonstrated that joint timber-carbon production can bring more income to landowners and that increasing carbon sequestration in the forest can be effective in mitigating greenhouse gas emissions. This study demonstrated that forest landowners might register for carbon projects and keep their benefits from the timber trade. In addition, in the joint timber-carbon scenario, carbon income offers landowners some protection against large changes/decline in timber prices. Carbon market developments indicate that carbon markets will continue to grow in the coming years (Blaufelder et al., 2021). Landowners can gain extra profit in addition to profit realized from the timber harvest by learning how carbon markets operate and being open to innovations in forest business management. Although current carbon prices for IFM projects are not at the desired level, they are expected to grow in the future. If prices increase, carbon trade might be at a level where it can effectively compete with timber income. Should that happen, forest management may become increasingly driven by carbon values.

5 CONCLUSION

Forest-based mitigation of greenhouse gas emissions through improved forest management, genetically improved seedlings, and using wood products could have a significant positive result when applied on a global scale. Joint timber-carbon production can help landowners generate more profit from their lands compared with traditional timber production while having an environmental effect on mitigating global warming.

Different climate conditions and geographical features will require working with different tree species. More-

over, there are many carbon registries with various methodologies. The U.S. participation in international climate action depends on numerous factors and on the government and political processes that determine participation in various global climate initiatives. This impacts support for potential carbon trade approaches or tax relief efforts for those who undertake forest carbon projects. Future studies may shed light on the profitability of the joint timber-carbon production approach under various conditions.

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APPENDIX A: SUPPLEMENTARY TABLES

Table A.1 Yield by product classes of four genotypes (ton/acre/year).

Age	OP-Control				OP-Average				CMP-Average				Variety			
	PW	CNS	ST	Poles	PW	CNS	ST	Poles	PW	CNS	ST	Poles	PW	CNS	ST	Poles
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.6	0.0	0.0	0.0
2	0.9	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	1.5	0.0	0.0	0.0
3	2.2	0.0	0.0	0.0	2.7	0.0	0.0	0.0	3.3	0.0	0.0	0.0	3.7	0.0	0.0	0.0
4	5.3	0.0	0.0	0.0	6.3	0.0	0.0	0.0	7.5	0.0	0.0	0.0	8.4	0.0	0.0	0.0
5	11.3	0.0	0.0	0.0	13.3	0.0	0.0	0.0	15.3	0.0	0.0	0.0	17.0	0.0	0.0	0.0
6	21.4	0.0	0.0	0.0	24.8	0.0	0.0	0.0	27.9	0.0	0.0	0.0	30.6	0.1	0.0	0.0
7	32.4	0.0	0.0	0.0	37.2	0.1	0.0	0.0	41.4	0.4	0.0	0.0	44.5	1.1	0.0	0.0
8	43.7	0.2	0.0	0.0	49.9	0.3	0.0	0.0	54.4	1.6	0.0	0.0	56.6	4.2	0.0	0.0
9	54.7	0.5	0.0	0.0	62.2	0.8	0.0	0.0	66.2	3.8	0.0	0.0	66.2	9.9	0.0	0.0
10	65.5	1.1	0.0	0.0	74.1	1.6	0.0	0.0	76.9	7.2	0.0	0.0	73.3	17.7	0.0	0.0
11	75.6	1.8	0.0	0.0	85.5	2.5	0.0	0.0	86.2	11.4	0.0	0.0	78.4	27.2	0.0	0.0
12	85.3	2.6	0.0	0.0	96.4	3.5	0.0	0.0	94.4	16.2	0.0	0.0	81.9	37.9	0.0	0.0
13	94.6	3.5	0.0	0.0	106.7	4.6	0.0	0.0	101.6	21.5	0.0	0.0	84.0	49.2	0.0	0.0
14	103.4	4.4	0.0	0.0	116.5	5.8	0.0	0.0	108.0	27.3	0.0	0.0	85.1	61.1	0.0	0.0
15	32.5	25.2	0.4	0.1	31.4	27.6	0.6	0.1	26.4	35.5	1.3	0.3	23.1	40.5	2.3	0.6
16	33.0	32.0	1.1	0.3	31.9	33.8	1.4	0.4	26.1	42.4	2.9	0.7	22.4	47.1	5.1	1.3
17	34.5	39.1	2.5	0.6	33.5	39.3	3.5	0.9	26.9	47.7	6.5	1.6	22.7	51.2	10.3	2.6
18	35.8	43.0	5.1	1.3	35.3	44.3	6.8	1.7	28.0	51.4	12.0	2.9	23.2	53.1	18.4	4.6
19	39.3	46.4	7.4	1.8	38.9	45.0	11.8	3.0	30.4	51.2	19.5	4.7	24.4	51.7	28.0	7.0
20	42.5	48.5	9.9	2.5	42.4	45.5	16.3	4.1	32.9	50.7	26.2	6.3	25.9	50.2	37.0	9.3
21	45.7	48.5	13.0	3.3	45.9	45.6	20.6	5.2	35.5	49.6	33.0	8.0	27.5	48.3	45.7	11.4
22	49.8	48.6	15.9	4.0	49.9	44.2	25.4	6.4	38.4	47.6	39.8	9.6	29.0	46.4	53.9	13.5
23	53.7	48.8	18.5	4.6	53.7	42.9	29.8	7.5	41.1	45.8	46.2	11.2	30.5	44.7	61.8	15.4
24	57.3	48.9	21.1	5.3	57.1	41.9	34.0	8.5	43.6	44.1	52.4	12.7	31.9	43.0	69.4	17.4
25	60.7	49.1	23.5	5.9	60.7	40.7	38.0	9.5	46.1	42.5	58.2	14.1	33.3	41.4	76.7	19.2
26	64.0	49.2	25.9	6.5	64.0	39.6	41.8	10.4	48.4	41.0	63.9	15.5	34.6	40.0	83.6	20.9
27	67.3	49.1	28.3	7.1	67.1	38.7	45.5	11.4	50.8	39.5	69.4	16.8	35.9	38.5	90.4	22.6
28	70.5	48.9	30.6	7.6	70.3	37.6	49.1	12.3	53.0	38.2	74.6	18.1	37.1	37.5	96.7	24.2
29	73.6	48.6	32.9	8.2	73.3	36.8	52.6	13.1	55.0	37.4	79.4	19.2	38.2	36.6	102.8	25.7
30	76.6	48.2	35.3	8.8	76.0	36.2	55.8	13.9	56.9	36.6	84.2	20.4	39.2	35.8	108.9	27.2
31	79.4	47.9	37.6	9.4	78.8	35.6	59.0	14.7	58.9	35.9	88.9	21.5	40.3	34.9	114.8	28.7
32	82.3	47.4	39.8	10.0	81.5	35.1	62.2	15.5	60.8	35.1	93.5	22.6	41.5	33.9	120.6	30.2
33	85.1	46.9	42.0	10.5	84.2	34.5	65.3	16.3	62.7	34.2	98.0	23.7	42.5	32.8	126.4	31.6
34	87.9	46.3	44.3	11.1	86.8	33.8	68.3	17.1	64.5	33.2	102.5	24.8	43.5	31.8	132.2	33.0

Table A.1 (continued)

Age	OP-Control				OP-Average				CMP-Average				Variety			
	PW	CNS	ST	Poles	PW	CNS	ST	Poles	PW	CNS	ST	Poles	PW	CNS	ST	Poles
35	90.7	45.6	46.6	11.6	89.4	33.1	71.4	17.8	66.4	32.3	107.0	25.9	44.5	30.8	137.8	34.4
36	93.4	45.0	48.8	12.2	91.9	32.3	74.4	18.6	68.2	31.4	111.5	27.0	45.6	29.8	143.3	35.8
37	96.2	44.4	51.0	12.7	94.5	31.6	77.5	19.4	69.9	30.5	115.8	28.0	46.5	28.9	148.7	37.2
38	98.9	43.7	53.1	13.3	97.1	30.9	80.5	20.1	71.7	29.5	120.0	29.0	47.6	27.8	154.3	38.6
39	101.5	43.0	55.3	13.8	99.5	30.1	83.4	20.8	73.4	28.6	124.3	30.1	48.5	26.8	159.7	39.9
40	104.1	42.2	57.5	14.4	101.9	29.4	86.3	21.6	75.1	27.6	128.6	31.1	49.4	25.7	165.0	41.2
41	106.6	41.3	59.6	14.9	104.3	28.5	89.1	22.3	76.8	26.5	132.8	32.1	50.3	24.7	170.2	42.5
42	109.2	40.4	61.8	15.4	106.8	27.7	92.0	23.0	78.5	25.5	136.9	33.1	51.3	23.6	175.2	43.8
43	111.8	39.5	63.9	16.0	109.2	26.8	94.9	23.7	80.1	24.5	140.9	34.1	52.2	22.6	180.4	45.1
44	114.2	38.6	66.0	16.5	111.5	25.9	97.7	24.4	81.7	23.5	144.9	35.0	53.0	21.6	185.6	46.4
45	116.8	37.5	68.0	17.0	113.8	25.0	100.4	25.1	83.3	22.5	148.9	36.0	53.7	20.9	190.4	47.6
46	119.4	36.3	70.2	17.5	116.0	24.1	103.2	25.8	84.9	21.4	153.0	37.0	54.5	20.4	194.9	48.7
47	121.9	35.2	72.3	18.1	118.3	23.1	105.9	26.5	86.3	20.8	156.6	37.9	55.2	19.9	199.3	49.8
48	124.3	34.4	74.3	18.6	120.6	22.2	108.6	27.2	87.7	20.3	160.2	38.8	55.9	19.4	203.7	50.9
49	126.7	33.6	76.2	19.1	122.9	21.3	111.3	27.8	89.1	19.8	163.6	39.6	56.6	18.8	208.1	52.0
50	129.1	32.8	78.1	19.5	124.9	20.8	113.8	28.4	90.4	19.3	167.0	40.4	57.3	18.3	212.5	53.1

Table A.2 Carbon accounting constants used in the analysis.

Parameter	Value	Source
Carbon fraction of dry biomass	0.50	IPCC (2006)
Root-to-shoot ratio	0.15	IPCC (2006)
Carbon to CO ₂ conversion factor	44/12	IPCC (2006)
Specific gravity (<i>Pinus taeda</i>)	0.47	USDA Forest Service (2003)
Outside-bark proportion	0.98	USDA Forest Service (2003)
Total tree factor	1.12	USDA Forest Service (2003)

Note: Constants are drawn from IPCC guidelines and USDA sources commonly used in forest carbon accounting.

Table A.3 Costs and benefits table of ACR joint timber-carbon production project (acre/year).

Year	OP-Average				CMP-Average				Variety			
	Mgmt. & seed.	ACR fees	Timber rev.	CO ₂ rev.	Mgmt. & seed.	ACR fees	Timber rev.	CO ₂ rev.	Mgmt. & seed.	ACR fees	Timber rev.	CO ₂ rev.
0	\$395.0	\$0.0	\$0.0	\$0.0	\$468.0	\$0.0	\$0.0	\$0.0	\$546.0	\$0.0	\$0.0	\$0.0
1	\$0.0	\$35.0	\$0.0	\$0.0	\$0.0	\$35.0	\$0.0	\$0.0	\$0.0	\$35.0	\$0.0	\$0.0
2	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
3	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
4	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
5	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
6	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.1	\$0.0	\$9.0
7	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$4.9	\$0.0	\$0.0	\$0.0	\$5.3	\$0.0	\$18.7
8	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.1	\$0.0	\$0.5	\$0.0	\$5.3	\$0.0	\$16.8
9	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.1	\$0.0	\$7.2	\$0.0	\$5.3	\$0.0	\$19.7
10	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.1	\$0.0	\$7.2	\$0.0	\$5.2	\$0.0	\$14.9
11	\$0.0	\$6.9	\$0.0	\$125.6	\$0.0	\$8.0	\$0.0	\$199.5	\$0.0	\$8.1	\$0.0	\$210.0
12	\$0.0	\$9.3	\$0.0	\$284.6	\$0.0	\$9.4	\$0.0	\$295.1	\$0.0	\$9.6	\$0.0	\$306.6
13	\$0.0	\$10.6	\$0.0	\$377.4	\$0.0	\$10.8	\$0.0	\$387.9	\$0.0	\$10.9	\$0.0	\$396.5
14	\$0.0	\$12.0	\$876.1	\$466.3	\$0.0	\$12.1	\$1,081.4	\$477.8	\$0.0	\$12.3	\$1,331.0	\$485.5
15	\$72.0	\$5.0	\$0.0	\$0.0	\$72.0	\$5.0	\$0.0	\$0.0	\$72.0	\$5.0	\$0.0	\$0.0
16	\$87.0	\$5.0	\$0.0	\$0.0	\$87.0	\$5.0	\$0.0	\$0.0	\$87.0	\$5.0	\$0.0	\$0.0
17	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
18	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
19	\$0.0	\$8.5	\$0.0	\$235.4	\$0.0	\$8.1	\$0.0	\$205.7	\$0.0	\$7.7	\$0.0	\$178.4
20	\$0.0	\$11.1	\$0.0	\$410.9	\$0.0	\$11.2	\$0.0	\$417.6	\$0.0	\$11.4	\$0.0	\$427.1
21	\$0.0	\$12.1	\$0.0	\$473.0	\$0.0	\$12.2	\$0.0	\$482.6	\$0.0	\$12.3	\$0.0	\$487.4
22	\$395.0	\$17.9	\$2,517.1	\$863.5	\$468.0	\$18.5	\$2,999.4	\$899.6	\$546.0	\$18.9	\$3,435.8	\$928.5
23	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
24	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
25	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
26	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
27	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
28	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
29	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
30	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
31	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
32	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
33	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
34	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
35	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0

Table A.3 (continued)

Year	OP-Average				CMP-Average				Variety			
	Mgmt. & seed.	ACR fees	Timber rev.	CO ₂ rev.	Mgmt. & seed.	ACR fees	Timber rev.	CO ₂ rev.	Mgmt. & seed.	ACR fees	Timber rev.	CO ₂ rev.
36	\$0.0	\$5.0	\$876.1	\$0.0	\$0.0	\$5.0	\$1,081.4	\$0.0	\$0.0	\$5.0	\$1,331.0	\$0.0
37	\$72.0	\$5.0	\$0.0	\$0.0	\$72.0	\$5.0	\$0.0	\$0.0	\$72.0	\$5.0	\$0.0	\$0.0
38	\$87.0	\$5.0	\$0.0	\$0.0	\$87.0	\$5.0	\$0.0	\$0.0	\$87.0	\$5.0	\$0.0	\$0.0
39	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
40	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0	\$0.0	\$5.0	\$0.0	\$0.0
41	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0
42	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0
43	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0
44	\$0.0	\$0.0	\$2,517.1	\$0.0	\$0.0	\$0.0	\$2,999.4	\$0.0	\$0.0	\$0.0	\$3,435.8	\$0.0

Note: This table represents current values. *Abbreviations:* OP = Open Pollinated, CMP = Control Mass Pollinated, ACR = American Carbon Registry, Mgmt. = Management.

Table A.4a Cashflow table of joint timber-carbon production project for 100 acres (Years 0–11).

Year	0	1	2	3	4	5	6	7	8	9	10	11
OP-Average												
Mgmt. & seedling costs	\$39,500											
ACR Cost		\$3,500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$688
Timber Revenue												
CO2 Revenue		\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$12,556
Cash Flow	-\$39,500	-\$3,500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	\$11,868
CMP-Average												
Mgmt. & seedling costs	\$46,800											
ACR Cost		\$3,500	\$500	\$500	\$500	\$500	\$500	\$490	\$511	\$511	\$511	\$798
Timber Revenue												
CO2 Revenue		\$0	\$0	\$0	\$0	\$0	-\$807	-\$136	\$533	\$916	\$724	\$724
Cash Flow	-\$46,800	-\$3,500	-\$500	-\$500	-\$500	-\$500	-\$1,307	-\$626	\$22	\$405	\$214	-\$74
Variety												
Mgmt. & seedling costs	\$54,600											
ACR Cost		\$3,500	\$500	\$500	\$500	\$500	\$513	\$528	\$525	\$529	\$522	\$814
Timber Revenue												
CO2 Revenue		\$0	\$0	\$0	\$0	\$0	\$898	\$1,872	\$1,681	\$1,968	\$1,490	\$21,003
Cash Flow	-\$54,600	-\$3,500	-\$500	-\$500	-\$500	-\$500	\$385	\$1,344	\$1,156	\$1,438	\$967	\$20,189

Table A.4b Cashflow table of joint timber-carbon production project for 100 acres (Years 12–22).

Year	12	13	14	15	16	17	18	19	20	21	22
OP-Average											
Mgmt. & seedling costs				\$7,200	\$8,700						\$39,500
ACR Cost	\$926	\$1,064	\$1,197	\$500	\$500	\$500	\$500	\$852	\$1,114	\$1,207	\$1,791
Timber Revenue			\$87,613								\$251,713
CO2 Revenue	\$28,463	\$37,740	\$46,634	\$0	\$0	\$0	\$0	\$23,542	\$41,087	\$47,304	\$86,347
Cash Flow	\$27,537	\$36,675	\$133,050	-\$7,700	-\$9,200	-\$500	-\$500	\$22,690	\$39,973	\$46,097	\$296,768
CMP-Average											
Mgmt. & seedling costs				\$7,200	\$8,700						\$46,800
ACR Cost	\$941	\$1,080	\$1,214	\$500	\$500	\$500	\$500	\$808	\$1,124	\$1,222	\$1,845
Timber Revenue			\$108,142								\$299,942
CO2 Revenue	\$724	\$19,950	\$29,515	\$0	\$0	\$0	\$0	\$20,574	\$41,757	\$48,260	\$89,962
Cash Flow	-\$217	\$18,870	\$136,443	-\$7,700	-\$9,200	-\$500	-\$500	\$19,766	\$40,632	\$47,039	\$341,259
Variety											
Mgmt. & seedling costs				\$7,200	\$8,700						\$54,600
ACR Cost	\$958	\$1,093	\$1,226	\$500	\$500	\$500	\$500	\$767	\$1,139	\$1,229	\$1,888
Timber Revenue			\$133,097								\$343,583
CO2 Revenue	\$30,662	\$39,653	\$48,547	\$0	\$0	\$0	\$0	\$17,840	\$42,713	\$48,738	\$92,845
Cash Flow	\$29,704	\$38,560	\$180,418	-\$7,700	-\$9,200	-\$500	-\$500	\$17,073	\$41,574	\$47,510	\$379,940

Table A.4c Cashflow table of joint timber-carbon production project for 100 acres (Years 23–33).

Year	23	24	25	26	27	28	29	30	31	32	33
OP-Average											
Mgmt. & seedling costs											
ACR Cost	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Timber Revenue											
CO2 Revenue	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Cash Flow	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500
CMP-Average											
Mgmt. & seedling costs											
ACR Cost	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Timber Revenue											
CO2 Revenue	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Cash Flow	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500
Variety											
Mgmt. & seedling costs											
ACR Cost	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Timber Revenue											
CO2 Revenue	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Cash Flow	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500	-\$500

Table A.4d Cashflow table of joint timber-carbon production project for 100 acres (Years 34–44).

Year	34	35	36	37	38	39	40	41	42	43	44
OP-Average											
Mgmt. & seedling costs				\$7,200	\$8,700						
ACR Cost	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Timber Revenue			\$87,613								\$251,713
CO2 Revenue	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Cash Flow	-\$500	-\$500	\$87,113	-\$500	-\$500	-\$500	-\$500	\$0	\$0	\$0	\$251,213
CMP-Average											
Mgmt. & seedling costs				\$7,200	\$8,700						
ACR Cost	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Timber Revenue			\$108,142								\$299,942
CO2 Revenue	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Cash Flow	-\$500	-\$500	\$107,642	-\$500	-\$500	-\$500	-\$500	\$0	\$0	\$0	\$299,442
Variety											
Mgmt. & seedling costs				\$7,200	\$8,700						
ACR Cost	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Timber Revenue			\$133,097								\$343,583
CO2 Revenue	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Cash Flow	-\$500	-\$500	\$132,597	-\$500	-\$500	-\$500	-\$500	\$0	\$0	\$0	\$343,083

Note: This table represents current values. *Abbreviations:* OP = Open Pollinated, CMP = Control Mass Pollinated, ACR = American Carbon Registry, Mgmt. = Management.

SUPPLEMENT 3. SOURCE DATA FOR FIGURES

The following tables provide the underlying data for Figures 1–3.

Table S3.1 Source data for Figure 1: merchantable yield (ton/acre) over two 22-year rotations.

Age	OP-Control	OP-Average	CMP-Average	Variety
0	0.0	0.0	0.0	0.0
1	0.3	0.4	0.5	0.6
2	0.9	1.0	1.3	1.5
3	2.2	2.7	3.3	3.7
4	5.3	6.3	7.5	8.4
5	11.3	13.3	15.3	17.0
6	21.4	24.8	27.9	30.7
7	32.4	37.3	41.8	45.6
8	43.9	50.2	56.0	60.8
9	55.2	63.0	70.0	76.1
10	66.6	75.7	84.1	91.0
11	77.4	88.0	97.6	105.6
12	87.9	99.9	110.6	119.8
13	98.1	111.3	123.1	133.2
14	107.8	122.3	135.3	146.2
15	58.2	59.7	63.5	66.5
16	66.4	67.5	72.1	75.9
17	76.7	77.2	82.7	86.8
18	85.2	88.1	94.3	99.3
19	94.9	98.7	105.8	111.1
20	103.4	108.3	116.1	122.4
21	110.5	117.3	126.1	132.9
22	118.3	125.9	135.4	142.8
23	0.3	0.4	0.5	0.6
24	0.9	1.0	1.3	1.5
25	2.2	2.7	3.3	3.7
26	5.3	6.3	7.5	8.4
27	11.3	13.3	15.3	17.0
28	21.4	24.8	27.9	30.7
29	32.4	37.3	41.8	45.6
30	43.9	50.2	56.0	60.8
31	55.2	63.0	70.0	76.1
32	66.6	75.7	84.1	91.0
33	77.4	88.0	97.6	105.6
34	87.9	99.9	110.6	119.8
35	98.1	111.3	123.1	133.2
36	107.8	122.3	135.3	146.2
37	58.2	59.7	63.5	66.5
38	66.4	67.5	72.1	75.9
39	76.7	77.2	82.7	86.8
40	85.2	88.1	94.3	99.3
41	94.9	98.7	105.8	111.1
42	103.4	108.3	116.1	122.4
43	110.5	117.3	126.1	132.9
44	118.3	125.9	135.4	142.8

Table S3.2 Source data for Figure 2: land expectation value (\$/acre) by stand age.

Age	OP-C	OP-A	CMP-A	Variety	Age	OP-C	OP-A	CMP-A	Variety
1	-382	-395	-468	-546	27	639	822	1041	1255
2	-6687	-6896	-8165	-9523	28	620	803	1019	1231
3	-3383	-3491	-4125	-4814	29	598	780	994	1203
4	-2240	-2289	-2706	-3166	30	577	757	965	1171
5	-1589	-1605	-1900	-2233	31	555	731	937	1140
6	-1100	-1079	-1295	-1542	32	533	706	908	1106
7	-666	-610	-766	-946	33	511	682	878	1072
8	-349	-267	-370	-499	34	488	656	848	1037
9	-113	-16	-75	-150	35	466	631	817	1003
10	54	165	145	133	36	444	606	788	969
11	182	299	320	355	37	423	581	759	934
12	268	392	447	531	38	403	558	729	901
13	329	456	540	665	39	383	534	700	868
14	370	497	605	760	40	363	511	673	835
15	394	521	651	829	41	344	489	645	803
16	516	627	748	877	42	325	466	618	772
17	516	617	749	893	43	307	445	592	741
18	586	681	830	983	44	289	424	566	711
19	632	751	917	1093	45	272	404	541	683
20	667	810	993	1180	46	255	384	517	654
21	686	842	1035	1239	47	239	365	494	626
22	690	859	1065	1273	48	224	347	471	599
23	690	867	1077	1290	49	210	329	449	573
24	683	865	1080	1294	50	195	312	428	548
25	672	855	1073	1290	51	181	296	407	523
26	657	841	1059	1276					

Table S3.3 Source data for Figure 3:
harvested timber volume (ton/acre).

Harvest	OP-A	CMP-A	Variety
Thinning	139.0	158.8	175.8
Clear-cut	251.8	270.8	285.6