Economic Tradeoffs in Timber Products Under Various Carbon Management Strategies for Pennsylvania

Submitted to
Penn Soil Resource Conservation and Development Council,
Pennsylvania, USA

Prepared for
Pennsylvania Department of Conservation and Natural Resources
Harrisburg, Pennsylvania

Prepared by
Raju Pokharel, Shivan Gc, Chad Papa, and Kylie Clay
Michigan State University

August 2024

Acknowledgement:

Penn Soil Resource Conservation and Development Council, Pennsylvania, USA
USDA Forest Service
Northern Institute of Applied Climate Science (NIACS), USDA Forest Service
Pennsylvania Department of Conservation and Natural Resources, Harrisburg, Pennsylvania
Forest Carbon and Climate Program, Department of Forestry, Michigan State University

Table of Contents

List of Tables

List of Figures

Overview

This report provides a financial trade-off analysis between costs associated with implementation of climate-smart forest management practices and potential incomes derived from carbon-based payment programs and timber products for the states of Pennsylvania. To do so, we use results published in Papa et al, (2023) in which researchers participatorily engaged with state forestry personnel and utilized a systems-based approach to quantify the climate mitigative potential of key climate-smart forest management and wood utilization strategies in support of net-zero emission reduction targets in Maryland and Pennsylvania. Papa et al, (2023) employed the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to model a broad range of forward-looking climate-smart forest management approaches. Additionally, the study uses a customized lifecycle harvest wood products model (CBM-HWP-PA) to conduct a sector-wide accounting of carbon emissions in the forest product sectors utilizing regional displacement factors, leakage rates, and wood product information to assess potential trade-offs between forest ecosystem and harvest wood product (HWP) mitigation potential. Summaries and implications for decision-makers from this study can be found in DeLyser et al, (2023a) and DeLyser et al, (2023b).

This report builds off those findings to further assist states in making informed decisions for optimizing trade-offs between climate-smart forestry practices and the economic benefits of timber products by providing estimations of potential costs and revenues associated with altering management approaches to boost the climate benefits of forests. The specific objectives of this study are to:

1. Convert the carbon (tC) results from Papa et al, (2023) into standing timber and wood product outputs (bd.ft. and cu.ft.);
2. Quantify the financial tradeoffs of both carbon and timber product-based income potential and associated costs resultant the alternate management and wood utilization scenarios as compared to a business-as usual (BAU) scenario.

To do this, we engaged with key state forest agency personnel to select specific alternative management and wood utilization scenarios described in detail in Papa et al, (2023) which include:

- Business-as-usual (BAU)
- Extending rotations*

- Increasing afforestation (four scenarios in total)*
- Increasing restocking of understocked stands*
- Increasing timber stand improvement (TSI)*
- Maintaining forest land base (Reduced deforestation)*
- Reduced diameter limit harvesting (e.g., unsustainable high grades)*
- Controlling deer browse*
- Silvopasture*
- No harvesting activities
- Portfolio (concurrent implantation of scenarios marked with *)

In general, this study conducts a comparative analysis of various modeled scenarios (change in management activities and land use) with BAU scenario using the net present value (NPV) approach. To achieve the outlined objectives, following activities were conducted in order:

1. Engagement with key stakeholders including state forest agency personnel, USDA Forest Service, Penn Soil Resource Conservation & Development Council, and other topical experts to discuss the scope of project outcomes, expectations from the project, and procedures to be adopted for accomplishing the project.
2. Following initial engagements, we discussed with key project partners the CBM-CFS3 results published in Papa et al, (2023) to better understand the implications and decision-support applications of these results that would be beneficial in a subsequent financial trade-off analysis.
3. Engagement with project partners in both states (Maryland and Pennsylvania) along with a thorough review of relevant literature to discuss costs, revenues, and carbon pricing to be used for the financial trade-off analysis.
4. Finally, we engaged with project partners to review the initial findings, understand potential implications, and to provide feedback on the outcomes obtained. Additionally, an excel workbook tool was created to allow for

In the following sections, we first outline integral background information to understand the role of forests in providing climate mitigation benefits and potential economic implications for landowner decision-making and management. Second, we briefly discuss methods employed in Papa et al, (2023) and outline which scenarios were chosen for the subsequent economic tradeoff analysis in detail, further discussing the data and methods employed for economic analysis. Third, we provide results and discussion for the financial trade-offs under various carbon management strategies along with a sensitivity analysis of carbon pricing. Lastly, we provide key implications and take-aways.

This study was made possible by a cooperative agreement between Penn Soil RC&D and the USDA Forest Service State, Private, and Tribal Forestry Eastern Region. This report focuses on the economic tradeoff analysis and results for Pennsylvania. A comparable report has been prepared for Maryland.

Background

Forests are increasingly recognized for their role in combatting climate change as they sequester and store atmospheric carbon dioxide (CO_2) in different repositories, known as carbon pools. These pools include above and below ground biomass, deadwood, litter, and soils where storage length can vary from years to decades to centuries, dependent on the pool. Forests also release carbon back into the atmosphere through processes such as respiration, combustion, and decomposition. In addition to respiration and decay, carbon can leave the forest via timber harvests and enter the forest products sector. Carbon that leaves the ecosystem through harvests or other management practices can be stored for years to decades in wood products significantly boosting the climate mitigation potential of forests. Eventually, this carbon returns to the atmosphere upon landfill disposal and decomposition.

In the Unites States, forests have acted as a net carbon sink since the early 1990s (Hoover and Riddle 2022) with forest productivity increasing throughout the early 21st century in eastern forests in part driven by climate change. In 2021, forests in the United States sequestered 760.1 MMT CO_2e which represents an offset of approximately 12.4% of the gross greenhouse gas emissions. Both forest management decisions and changing climatic conditions can have profound effects on a forests' capacity to sequester and store carbon. However, future trends forest carbon dynamics remain unclear due to anthropogenic disturbances, legacies of past management, and future vulnerabilities to climate change necessitating a greater understanding how carbon benefits from forests can be bolstered today and in the future.

While managing for forest carbon is of high priority, carbon is only one of many ecosystem services that forests provide. Climate-smart forestry, a targeted approach to bolster the mitigative potential of forests through increasing forest adaptation and resilience in addition to climate benefits from the use of wood, provides an effective strategy to balance both short and long-term goals. Common forest mitigation strategies include lengthening the average rotation age of working forestlands, increasing rates of afforestation and reforestation, avoiding conversion of forests to non-forest lands, protecting areas of high carbon and ecological value, fire resilience treatments, or boosting forest recovery through target actions such as underplanting on stands of low productivity.

Each potential management strategy as inherent trade-offs between management goals that may not manifest for years to decades. For example, increasing the average rotation age of a working forest stand can increase the carbon stored, but doing so, can have complex implications for potential increases in management costs, future landowner income, and other co-benefits derived from forests. Alternatively, certain forest health strategies such as prescribed fire have significant costs associated with them and can lead to an immediate decrease in carbon storage but provide a suite of other forest co-benefits including habitat restoration, reduced risk to disturbance, or future forest resilience.

Federal and state forest agencies are in a unique position to bolster the climate benefits of forests through their influence on forest management practices on state managed lands and through technical assistance and financial incentives on privately managed lands. Many states provide incentives in the form of tax breaks, cost share programs, and technical assistance to private forest landowners for promoting sustainable management of their forests. Increasingly states are looking for ways to promote climate-smart forest practices that balance climate specific management goals (e.g., increased carbon sequestration and storage, future forest resiliency) with more traditional management goals (e.g., timber production and income derivation). Given this, timely and appropriate forest carbon management interventions could be crucial for building forests' resilience and enhancing forests capacity to adapt to novel conditions and for promoting long-term carbon storage. To do so, forest managers and decisionmakers need accurate and updated information to properly asses the trade-offs between different management strategies in an effort better support and implement climate-smart forest practices.

Recent growth in both voluntary carbon and cap-and-trade markets further complicates landowner decision-making as these emerging markets provide potential new financial opportunities for forest landowners. Several economic barriers lie in the way of the successful implementation of forest carbon management strategies. Forest carbon management practices often require landowner investment while providing limited economic returns, especially in relation to alternative practices aimed at generating timber revenues. Therefore, to make meaningful carbon management decisions, an assessment of benefits versus costs under different management strategies is needed. Further assessments of the financial implications of the scenarios involving land managers' goals and the complex ecological process is needed to understand the economic feasibility of forest carbon programs.

Data and methods employed

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) modeling framework

The CBM-CFS3 is an operational-scale forest carbon model designed to simulate the dynamics of forest carbon stocks over time within IPCC compliant method (Kull et al, 2019, Kurz and Apps, 1999, Kurz et al, 2009). The model incorporates both human activities and natural disturbances to simulate forest C dynamics on annual timesteps. Although this model was originally developed as a core component of Canada's national GHG monitoring system (Kurz et al, 2018), it has been widely utilized internationally and domestically (Kurz et al, 2013, Pilli et al, 2013, 2017, 2022, Dugan et al, 2017, 2018a, 2018b, 2021, Oguin et al, 2018, Sleeter et al, 2022, Papa et al, 2023) and has been thoroughly verified against inventory plots (Shaw et al, 2014). The CBM-CFS3 utilizes spatially-referenced forest inventory data and empirically-derived volume-age curves to predict forest productivity. User defined schedules of management activities including harvests, natural disturbances, and land-use change (LUC) along with volume-biomass equations and processed-based equations to estimate annual carbon turnover and decay are used to simulate forest carbon trends. Simulations in Papa et al, (2023) were run from 2007-2100 with 2007-2019 being parameterized using historical data and the 2020-2100 period using longer-term averages to parameterize forward-looking projections.

ANSE model framework and CBM-HWP-PA data assumptions

Carbon that leaves the forest ecosystem via harvest, LUC, or other management actions are tracked in the regionally parameterized CBM-HWP-PA model. This model was built using the Abstract Network Simulation Engine (ANSE) modeling framework. ANSE is a carbon accounting tool developed by the Canadian Forest Service (CFS) and used for Canada's national GHG inventory reporting in tandem with the CBM-CFS3. The modeling framework facilitates tracking, modeling, and calculation of embodied carbons storage and emissions associated with HWP and the forest products sector.

Once carbon is transferred from the forest ecosystem to the forest product sectors, carbon is then partitioned among various wood product streams based on current practices. Carbon is either exported, retained for domestic use, or immediately used for mill residues, energy, and additional commodity production. Carbon is partitioned into distinct products stream determined by species and wood type. Each product stream has a corresponding half-life that determines the in-use residence time before being allocated to an end-of-life path including recycling, burned for energy, or landfill disposition. The CBM-HWP-PA also track inherited wood products, or products in-use, prior to model simulation starting from 1950 onwards.

In addition to emissions estimated from both the forest ecosystem and forest products, substitution (e.g., displace emissions) were estimated for when HWPs are substituted for more emissions-intensive products (e.g., concrete and steel). The change in production is assumed to have an associated displaced emissions or a reduction in GHG emissions. Substitution benefits were applied only to saw logs, composite panels, and bioenergy products. Additionally, negative substation benefits were calculated when the inverse occurred (i.e., a decrease in wood product manufacturing). State-specific displacement factors were estimated and applied for softwood and hardwood saw logs and composite panels where the calculated factor is associated with LCA data for extraction, raw material transport, and manufacturing of both the HWP and the assumed alternative materials.

Leakage factors of 0%, 63.9% (Gan and McCarl, 2007) and 84.4% (Wear and Murray, 2004) were applied for scenarios that resulted in lower rates of harvest as compared to the BAU to estimate an assumed increase in harvest activities occurring outside of the study area compensating for a decrease in timber supply. Assuming a leakage factor of 63.9% means that the remaining 36.1% of reduced harvest rates are subject to additional emissions from non-wood materials. Leakage was only assumed to result from reduced in-state harvest whereas increased in-state harvests are assumed to result in increased wood utilization rather than reductions in out-of-state harvests.

Both methods for the CBM-CFS3 and CBM-HWP-PA were briefly summarized here. For longer descriptions of all data and assumptions used, please see Papa et al, (2023).

Description of forest management scenarios modeled in Pennsylvania

The core of this analysis and that of Papa et al, (2023) relied on the parameterization of a BAU scenario (**Table 1**) to provide the basis for comparison against alternative scenarios. The BAU represents a continuation of current management practices (i.e., harvests, thinnings, prescribed burns), land-use changes (afforestation and deforestation), and natural disturbances (i.e., wildfires, windthrow, and insect and disease outbreaks). In addition to the BAU scenario, alternative management scenarios were developed by changing specific parameters related to future management decisions or disturbance events (**Table 2**). Scenarios related to one specific practice or objective that were determined by an assessment of priorities and concerns for state-wife forest planning. Each individual scenario represents a single potential climate-smart management tactic. However, rarely would these be implemented in isolation. To better represent comprehensive forest climate action, we developed the portfolio scenario which represents an ensemble of all multiple concurrent actions.

Table 1**.** BAU ecosystem parameters for Pennsylvania. All carbon values are in metric tons (tC)

Pennsylvania			
Land-use change			
Forest loss	-10,453 ha yr^{-1}	Forest Gain	+3,454 ha yr^{-1}
Natural disturbances			
Wildfire	960 ha yr^{-1}	Disease	3,957 ha yr^{-1}
Insect defoliation	47,832 ha yr^{-1}	Abiotic (wind, animal)	5,053 ha yr^{-1}
Insect mortality	374 ha yr^{-1}		
Forest management practices			
Prescribed fire (~40% understory consumption)			
State forests			
Clearcut (90% merchantable biomass removal)	7,894 tC yr^{-1} (39,806 m^3 yr^{-1})	Group selection / overstory removal (30% merchantable biomass removal)	95,869 tC yr^{-1} (371,573 m^3 yr^{-1})
Shelterwood cut (50% merchantable biomass removal)	206,873 tC yr^{-1} (787,685 m^3 yr^{-1})	Thinning (30% merchantable biomass removal)	49,718 tC yr^{-1} (194,179 m^3 yr^{-1})
Private forests			
Clearcut (90% merchantable biomass removal)	49,462 tC yr^{-1} (245,280 m^3 yr^{-1})	Shelterwood cut (50% merchantable biomass removal)	173,546 tC yr^{-1} (591,618 m^3 yr^{-1})
Seed tree cut (70% merchantable biomass removal)	281,346 tC yr^{-1} (1,093,346 m^3 yr^{-1})	Group selection / overstory removal (30% merchantable biomass removal)	205,761 tC yr^{-1} (80,329 m^3 yr^{-1})
Diameter-limit-cut (70% merchantable biomass removal)	203,833 tC yr^{-1} (791,733 m^3 yr^{-1})	Thinning (30% merchantable biomass removal)	543,168 tC yr^{-1} (2,074,145 m^3 yr^{-1})
US Forest Service / other federal forests			
Shelterwood cut (50% merchantable biomass removal)	21,911 tC yr^{-1} (85,610 m^3 yr^{-1})	Thinning (30% merchantable biomass removal)	66 tC yr^{-1} (265 m^3 yr^{-1})
Group selection / overstory removal (30% merchantable biomass removal)	11,660 tC yr^{-1} (46,798 m^3 yr^{-1})		

Table 2. Alternative management scenario parameters for Pennsylvania. All carbon measurements are in metric tons (tC).

Scenario	Objective	Parameter to change	Parameter value change	Scenario impact
Extended Rotations*	Increase average harvest age of hardwood stands	Minimum age of allowable harvest	+30 years on all hardwoods to 2170	Hardwood rotations: 70-80 years→100-110 years
	Decrease average harvest age of aspen stands for wildlife habitat		-10 years on aspen to 2170	Aspen rotations: 40 years→30 years
Afforestation (afGGRA 2030)	Increase afforestation, following GGRA targets, to 2030	Annual afforestation rate	+2,376 acres/year to 2030; then return to BAU rate	+23,760 acres afforested
Afforestation (afGGRA 2050)*	Increase afforestation, following GGRA targets, to 2050	Annual afforestation rate	+2,376 acres/year to 2050; then return to BAU rate	+70,280 acres afforested
Afforestation Scale Up 2030 (afSU2030)	Increase afforestation, scaled up 10x GGRA targets, to 2030	Annual afforestation rate	+23,760 acres/year to 2030; then return to BAU rate	+237,600 acres afforested
Afforestation Scale Up 2050 (afSU2050)	Increase afforestation, scaled up 10x GGRA targets, to 2050	Annual afforestation rate	+23,760 acres/year to 2050; then return to BAU rate	+712,800 acres afforested
Silvopasture*	Increase silvopasture adoption (low-density planting of trees in pastureland; does not remove land from productive pasture use)	Annual silvopasture planting rate	+15,250 acres/year (0.5% of eligible acreage) to 2170	+2,287,500 acres in silvopasture system
Restocking (Restock)*	Increase supplemental planting to restocking understocked stands	Annual supplemental planting rate	+4,508 acres/year to 2170	+626,200 acres restocked
Timber Stand Improvements (TSI)*	Increase TSI and wildlife habitat treatments, following GGRA targets	Annual thinning rate	+14,892 acres/year to 2170	+2,223,800 acres thinned
		Annual prescribed fire (Rx fire) rate	+25,000 acres/year to 2170	+3,750,000 acres treated with Rx fire
Reduced Deforestation (Reduced Def)*	Decrease rate of permanent forest loss (deforestation), following GGRA targets	Annual deforestation rate	-5,149 acres/year to 2170	+772,450 acres conserved
Reduced Diameter Limit Cuts (Reduced DLC)*	Eliminate diameter limit cutting (DLC, i.e., high grading) on private lands; transition to sustainable selective harvests (modeled as seed tree cuts)	Annual DLC removals	-30,559 t C/year (15% of DLC in BAU) until DLC=0 in 2027; DLC removals remain at 0 to 2170	203,833 t C/year (27,960,055 cu ft/year) transitioned to sustainable selective harvests
		Annual seed tree removals	+30,559 t C/year until 2027 (transitioning removals from DLC to seed tree cut); seed tree removals remain at 485,078 t C/year to 2170	

Control Deer Browse (Control DB)*	Increase rates of successful deer browse control (i.e., fencing) to encourage better natural regeneration	Annual deer browse control rate	+14,459 acres/year to 2170	+1,985,496 acres controlled
No Harvest†	Reduce all harvest and thinning activities on all lands	Annual harvest rate	-100% acres/year to 2170	-100% acres/year of harvesting and thinning management practices
		Annual thinning rate	-100% acres/year to 2170	
		Annual DLC rate	-100% acres/year to 2170	
Portfolio	Ensemble of concurrent scenarios (marked with * above) to illustrate potential for Pennsylvania to fully leverage its forests as a natural climate solution	Minimum age of allowable harvest	+30 years on all hardwoods to 2170	Hardwood rotations: 70-80 years→100-110 years
			-10 years on aspen to 2170	Aspen rotations: 40 years→30 years
		Annual afforestation rate	+2,376 acres/year to 2050; then return to BAU rate	+70,280 acres afforested
		Annual silvopasture planting rate	+15,250 acres/year (0.5% of eligible acreage) until 2170	+2,287,500 acres in silvopasture system
		Annual supplemental planting rate	+4,508 acres/year to 2170	+626,200 acres restocked
		Annual thinning rate	+14,892 acres/year to 2170	+2,223,800 acres thinned
		Annual prescribed fire rate	+25,000 acres/year to 2170	+3,750,000 acres treated with prescribed fire
		Annual deforestation rate	-5,149 acres/year to 2170	+772,450 acres conserved
		Annual DLC removals	-30,559 t C/year (15% of DLC in BAU) until DLC=0 in 2027; DLC removals remain at 0 to 2170	203,833 t C/year (27,960,055 cu ft/year) transitioned to sustainable selective harvests
		Annual seed tree removals	+30,559 t C/year until 2027 (transitioning removals from DLC to seed tree cut); seed tree removals remain at 485,078 t C/year to 2170	
		Annual deer browse control rate	+14,459 acres/year to 2170	+1,985,496 acres controlled

†This scenario results in some level of carbon being transferred to the HWP sector from land-use change

Estimation of timber products generated under BAU and alternative management scenarios

The first objective of this project was to convert carbon outputs (metric tonnes) generated from HWP model under BAU and alternative management scenarios into timber product outputs (bd.ft. and cu.ft). For this, we worked with MSU FCCP team to obtain the results from the HWPs model in volume format. Carbon outputs from HWPs model were converted into volume estimates using the following equation:

$$Volume = \frac{(Carbon*2)}{Specific\ Gravity} \quad (1)$$

State-specific weighted specific gravities were used for conversion of softwood/hardwood component of forest types in each state. For Pennsylvania, the weighted specific gravity was estimated to be 0.39312572 for softwoods and 0.57964335 for hardwoods. For Maryland, the weighted specific gravity was 0.5075104 for softwoods and 0.51647761 for hardwoods. Fraction of the product that is wood fiber was obtained using the relationship provided by Smith et. al. (2006). Table 3 shows conversion factors employed for converting carbon obtained from the HWP model in different product stream categories into volume estimates in Pennsylvania. The total resulting harvested volume was obtained from MSU FCCP team in excel spreadsheet under nineteen different product categories broken down by hardwood and softwood species groups. Harvested volumes were reported for each year starting 2008 to 2100. Out of the nineteen product categories in which the volume harvested were reported in, six categories representing roundwood, sawn wood, and veneer were combined to form a logs category with volumes estimated in Mbf (Thousand board feet) for financial analysis. Likewise, six categories representing pulp products were combined into a single pulpwood category with volume estimated in tons for financial analysis. Four categories representing composite panels were combined with other industrial to form a composite panel category with volume estimated in MCF (Thousand cubic feet) which was then converted into tons using a conversion factor of 0.0329193 MCF per ton as per Winn et al. (2020). Bioenergy data was used as obtained for financial analysis and the volume is estimated in tons. Poles, posts, and piling data was also included as obtained for financial analysis and the volume is estimated in Mbf. The resulting timber product outputs for each CBM-CFS management scenarios are reported for four different time periods: short term (2023 to 2032), medium term (2023 to 2050), medium-long term (2023 to 2070) and long term (2023 to 2100).

Table 3. Conversion factors employed for converting carbon obtained from HWPs model in different product stream categories into volume estimates in Pennsylvania.

		Carbon Conversion Factor Calculations					Conversion Factors[4]	
Product	Unit	Cubic ft/unit	lbs/cubic foot[1]	lbs/unit[2]	% fiber[3]	lbs to tonne	C	V
Softwood								
Sawlogs	MBF	83.33333	24.53104	2044.254	1	0.000454	0.464046	2.154961
Veneer logs	MBF	--	--	--	--	--	--	--
Pulpwood	tons	--	--	2000	1	0.000454	0.454	2.202643
Composite Panels	MCF	1000	24.53104	24531.04	0.95	0.000454	5.29012	0.189032
Fuelwood	tons	--	--	2000	1	0.000454	0.454	2.202643
Posts, Poles, pilings	MBF	83.33333	24.53104	2044.254	1	0.000454	0.464046	2.154961
Other Industrial	MCF	1000	24.53104	24531.04	1	0.000454	5.568547	0.17958
Hardwood								
Sawlogs	MBF	83.33333	36.16974	3014.145	1	0.000454	0.684211	1.461537
Veneer logs	MBF	83.33333	36.16974	3014.145	0.96	0.000454	0.656843	1.522435
Pulpwood	tons	--	--	2000	1	0.000454	0.454	2.202643
Composite Panels	MCF	1000	36.16974	36169.74	0.96	0.000454	7.882111	0.12687
Fuelwood	tons	--	--	2000	1	0.000454	0.454	2.202643
Posts, Poles, pilings	MBF	--	--	--	--	--	--	--
Other Industrial	MCF	--	--	--	--	--	--	--

Pounds per cubic feet = specific gravity*62.4

1. For MBF and MCF units, this is the multiplication of the previous two columns (i.e., cubic ft/unit*lbs/cubic feet); for tons, this is simply 2000.
2. % from GTR 343 table D1; % for softwood and hardwood plywood used for ‘composite panels’; assuming fuelwood and pulpwood are 100% fiber (not in GTR 343)
3. Conversion factor product units are product-specific (defined in column 2); carbon is in metric tons (tonnes)

Estimation of economic tradeoffs of timber products under alternative management scenarios compared to BAU

The next objective was to quantify the financial tradeoffs of carbon and timber products resulting from the alternative management scenarios compared to the BAU scenario modeled using CBM-CFS and HWPs model. For this, we first estimated the net present value of each forest carbon management scenario at four different time periods (short term (2023 to 2032), medium term (2023 to 2050), medium-long term (2023 to 2070), and long term (2023 to 2100) including the BAU. Then the NPV of each alternative forest carbon management scenario was compared with that of BAU to assess the economic tradeoffs.

The Net Present Value (NPV) is the difference between the present value of all revenues and costs associated with a particular forest management scenario (Bullard and Straka, 1998). It is also referred to as net benefit. In our case, revenues include income generated through the sale of timber products harvested as well as carbon credits generated under each forest carbon management scenario and costs include all costs associated with the implementation of that scenario including land rent. Land rent is the opportunity costs of using the land in forestry rather than for other alternative uses.

NPV is a useful financial tool to measure the economic feasibility of carbon management and can assist in informed decision making on policy interventions. Equations 2 presents the basic formulation of NPV. (2)

$$NPV = \sum \frac{R}{(1+i)^t} - \sum \frac{C}{(1+i)^t}$$

where, *R* is the revenue generated from the harvested wood products and/or carbon credits under each forest management scenario for the specified duration (short, medium, medium-long and long term). *C* is the costs associated with implementing each modeled management scenario including BAU for the same duration, *i* is the minimum acceptable real rate of return (RoR) and t is the time in years during the period considered.

Land rent can be estimated by multiplying the land expectation value (LEV) with the discount rate. LEV is the present value of all future net revenues from the land under perpetual forestry and can be estimated using the following formula:

$$LEV = \frac{NR}{(1+r)^T - 1} \quad (3)$$

where, *NR* is the net revenue at the end of a specified period, r is the discount rate and T is the rotation period or time until harvest. For estimating LEV, the rotation period of hardwood stands in Pennsylvania was chosen to be 80 years and that of softwoods stands was chosen to be 60 years after consultation with the project team.

Revenue Estimation

For BAU scenario, revenues were estimated for harvested wood products (logs, pulp products, composite panels, bioenergy, and poles/posts/pilings) by multiplying per unit stumpage price of the harvested wood product by the volume of that product harvested during a given year. For alternative management scenarios, revenues were estimated with and without taking into consideration the carbon emissions associated with these scenarios.

Carbon emissions associated with each management scenario were estimated using emission 64 and emission 84 leakage factors. (Please add a sentence or two explaining this). Carbon emissions were converted into carbon credits by multiplying emissions by per unit carbon price. For a given year, if more carbon was sequestered under an alternative management scenario compared to BAU, then the revenue generated from harvested wood products including carbon for that year would be higher than that estimated without taking into account carbon emissions.

Stumpage price information for harvested wood products in Pennsylvania was obtained from Pennsylvania DCNR. Average stumpage price of logs and pulpwood from 2016 to 2022 broken down by species groups were obtained from Pennsylvania DCNR and used as a baseline price for calendar year 2022. Table 4. lists the stumpage price information for different wood products by hardwood and softwood species groups used for financial analysis in PA. For 2022, the stumpage price of hardwood logs including poles, posts and pilings were estimated to be $253.87/Mbf. For pulpwood, composite panels, and bioenergy, the stumpage price was estimated to be $3.60/ton. Stumpage price of softwood logs including poles, posts, and pilings were estimated to be $94.10/Mbf and the price of softwood pulpwood, composite panels, and bioenergy was estimated to be $3.70/ton for 2022.

Though the stumpage price of poles, posts, and pilings are usually higher than that of logs in different parts of the country (Dickmann et al. 1997, Dickens et al. 2021), we chose to use the same stumpage price for logs and poles, posts, and pilings as it better represents the existing market practice in PA according to the project partners. Starting year 2023, stumpage prices were increased by 3% every year for hardwood species and 2.5% per year for softwood species for financial analysis. Percentage increase in timber prices for our analysis were based upon the historical timber price trends noted in PA from 2007 to 2017 by Jacobson (2022).

Table 4. Average stumpage price of different wood products in Pennsylvania from 2016 to 2021 by hardwood and softwood species group (Source: Pennsylvania DCNR).

Product Type	Stumpage Price	Unit
	Hardwood	
Logs & Poles, post, pilings	253.9	$/Mbf
Pulp	3.6	$/ton
	Softwood	
Logs & Poles, post, pilings	94.1	$/Mbf
Pulp	3.7	$/ton

To estimate revenue from carbon credits, market price of carbon for year 2022 was obtained from live carbon prices today, accessed online from a digital platform of nature-based carbon offset price maintained by carboncredits.com. For 2022, price per ton of CO_2 equivalent was $8.29 dollars (as accessed in Oct 6,2022). We deducted the transaction cost of carbon from its market price to get the price of carbon that was used for financial analysis. Transaction cost of carbon was estimated using the formula proposed by Pearson et al. (2013). According to the authors, transaction cost of carbon can be estimated using the following equation:

$TC = 1 + 0.23*P^c$

Where TC is the transaction cost of carbon, 1 represents the fixed cost of carbon ($1 per ton) and $0.23*P^c$ represents the variable cost of carbon which is assumed to be 23% of the market price of carbon. For our analysis, the carbon price was assumed to increase by 2% every year starting 2023. Additionally, sensitivity analysis was done with varying carbon prices ranging from $5/ton of CO_2 equivalent to $100/ton of CO_2 equivalent.

Cost estimation

Costs include expenses associated with implementing different forest management prescriptions outlined in the BAU and alternative management scenarios (Tables 1 and 2). Details of forest management practices carried out every year starting year 2008 to 2100 under each scenario were obtained from MSU FCCP team. This included information about the type of forest management practice undertaken each year and the acres the management practice was undertaken in. Per unit cost of each management practice was multiplied with the area of forest acres that underwent such practice to get the costs associated with implementing different management practices under various scenarios for financial analysis. Forest management practices included in case of BAU scenario are clearcut, group cut, high grade, seed tree, and shelterwood harvest along with thinning and prescribed burn treatments. For our analysis, we used the costs associated with carrying out thinning operations, prescribed fire treatment and site preparation as well as regeneration cost in clearcut areas under baseline BAU scenario. Costs associated with timber harvesting operations were not included in the analysis as these are assumed to be accounted for in the stumpage price of products harvested. Similar costs as those used in BAU scenario were incorporated in extended rotation scenario. For afforestation scenario, in addition to the costs used in business-as-usual scenario, afforestation costs were included. Likewise, for restocking scenario, costs associated with restocking the forest were added to the business-as-usual costs. For timber stand improvement, reduced deforestation and reduced diameter limit cut scenarios, again, similar costs as baseline scenario were included. In case of controlled deer browse scenario, additional cost of fencing to control for deer browse was included and for silvopasture scenario, silvopasture planting cost was included in addition to other costs as in business-as-usual scenario. In no harvest scenario, only the costs associated with prescribed burning was included.

Cost information about forest management practices in Pennsylvania needed for financial analysis was obtained from the Environmental Quality Incentives Program's (EQIP) payment schedule for Pennsylvania 2022 and is listed in Table 5. For clearcut area, we included site preparation cost of $221.7/acre and forest establishment cost of $813.7/acre for hardwood species group and $390.7/acre for softwood species group. Site preparation cost comes from-tree/shrub site preparation cost (EQIP Code 490) under PA EQIP payment schedule 2022. We estimated an average of hand site prep ($222.1/acre) and mechanical heavy ($221.4/acre). Forest establishment cost comes from tree/shrub establishment (Code 612) under PA EQIP 2022. For hardwoods, we used tree/shrub regeneration area with protection cost ($813.7/acre) and for softwoods, we used costs for medium density conifer planting ($390.7/acre). Thinning costs come from forest stand improvement (Code 666) under PA EQIP 2022. The cost included was for thinning hand tools with a consultant ($327.2/acre). Cost for prescribed burning comes from prescribed burning (Code 338) under PA EQIP 2022. The cost included was for understory burn ($76/acre).

Forest establishment cost for hardwood species group ($813.7/acre) was used as a proxy for afforestation cost since majority of the afforested acres (97%) in PA were in hardwood forest type group. Supplemental hardwood tree planting with shelters (Code 612) was used for estimating the restocking cost in PA. Again, this was done because most of the restocked acres (93%) in the state were in hardwood forests. Fencing cost for controlling deer browse for the year 2022 was estimated to be $387/acre. This is the cost required for fencing with woven wire at a cost of $3.28/linear feet (Obtained from PA EQIP Code 382) assuming 5,903 linear feet of fence is required for fencing 50 acres of forest area as per (Jacobson 2007). The cost information for establishing trees under silvopasture scenario was not available in PA EQIP payment schedule 2022 but the information was available for the same year for Maryland. Hence, after consultation with project partners, silvopasture tree establishment cost in Maryland was used as a proxy for cost in Pennsylvania. It was $127.63/acre for 2022.
Starting year 2023, all forest management practices costs were increased by 1.69% per year to account for inflation. The percentage chosen to account for inflation is based upon the average annual inflation rate estimated between the calendar years 2007 to 2017.

Table 5. Forest management practices costs in Pennsylvania (Source: Environmental Quality Incentives Program's (EQIP) payment schedule for Pennsylvania 2022).

Type of Forest Management Practice	EQIP Code	Per unit cost of implementing the management practice
Thinning	666	$327.2/acre
Prescribed fire	338	$75.95/acre
Site preparation cost in clearcut areas	490	$221.74/acre (Average of hand site prep and mechanical heavy)
Stand establishment cost in clearcut areas	612	$813.70/acre for hardwood species and $390.67/acre for softwood species
Afforestation cost	612	$813.70/acre
Restocking cost	612	$636.20/acre
Fencing cost	382	$387/acre
Silvopasture planting cost	381	$128/acre

Results and Discussion

Area and volume harvested under different scenarios

The first objective of this project was to quantify the volume of timber products resulting from the HWPs model under BAU and alternative carbon management scenarios. But before moving on to the estimate of area and volume harvested under each forest management scenario, it should be noted that the total forest area projected by CBM-CFS models under BAU and most of the alternative carbon management scenarios declined consistently from 2023 to 2100 owing to forest loss (Appendix A). The only carbon management scenario under which projected forest area consistently increased was the portfolio scenario. Projected forest area under both scaled up afforestation scenarios increased until the specified afforestation duration (2030 and 2050 respectively) and declined after that. The rate of decline in projected forest area was the least for silvopasture scenario compared to other scenarios including BAU. For more information on projected forest areas under different carbon management scenarios, please refer to Papa et al, (2023).

The total forest area harvested each year under BAU and alternative carbon management scenarios from 2023 to 2100 and volume harvested each year under the same scenarios are listed in Appendix B and C respectively. Forest area harvested each year under BAU scenario ranged from a high of 193 thousand acres in 2026 to a low of 134 thousand acres in 2090. Harvested area under BAU was relatively higher in the first two decades compared to the later years. Similar trend was observed in the volume harvested under BAU. The total volume harvested each year under BAU ranged from a high of 11.6 million tons in 2039 to a low of 9.5 million tons in 2089. Compared to BAU, the area harvested under extended rotation scenario decreased initially for approximately the first decade and increased after that. Volume harvested under extended rotation scenario also lagged behind BAU for the first 25 years, was close to BAU for the next few years and slightly exceeded it in the later years. This seems logical since extended rotation scenario pushes the rotation age of hardwood forest stands in Pennsylvania by 30 years (except for Aspen stands, whose rotation age declines by ten years under this scenario). Since the rotation age of hardwood stands is pushed back, the area and volume harvested declines initially but catches up eventually as trees grow larger in size and reach the new rotation age for harvest.

Area harvested each year under all four cases of afforestation scenarios trailed close to that of BAU scenario for the most part with slightly higher area harvested under afforestation scaled up

2050 scenario after 2075. Volume harvested under all four cases of afforestation scenarios were also close to that of BAU scenario at all time frames considered. Likewise, the area and volume harvested under restocking scenario closely resembled that of BAU scenario till 2100. In case of TSI scenario, both the area and volume harvested almost consistently exceeded that of BAU at all timeframes considered. This makes sense as area thinned under TSI scenario is greater than that under business-as-usual scenario. Besides, forest management prescriptions implemented under TSI scenario are likely to improve the growth rate of remaining forest stands thus yielding greater volume compared to BAU scenario.

Area and volume harvested each year under reduced deforestation scenario were in general slightly lower than that of the BAU. In the case of reduced diameter limit cut scenario, the area and volume harvested each year were initially close to BAU scenario, but as the years progressed (after the first two decades), the gap in area and volume harvested widened considerably between the two scenarios in favor of reduced DLC scenario. Area and volume harvested per year under controlled deer browse scenario resembled that of BAU scenario. Area harvested under portfolio scenario was slightly lower than BAU for the first two decades, followed close to BAU for the next several years and slightly exceeded BAU area harvested in the last decade whereas the volume harvested under portfolio scenario was slightly lower than that of BAU for the entire duration. In case of Silvopasture scenario, the area harvested each year resembled that of BAU scenario till 2064, after which it increased slightly. Volume harvested under Silvopasture scenario also generally resembled that of BAU scenario with slight increase in the later years. Area and volume harvested under no harvest scenario were much less than that under BAU scenario as expected.

Of the timber products harvested each year under all scenarios in Pennsylvania, about half were pulpwood (49.1% on average), 38.5% were logs, 7.5% were composite panels, 4.6% were bioenergy and the remaining 0.2% were pole, posts, and pilings.

For financial analysis, we considered the total forest area and volume harvested under each management scenario for four different time frames, short term (starting from 2023 to 2032), medium term (starting from 2023 to 2050), medium-long term (starting from 2023 to 2070) and long term (starting from 2023 to 2100). The results obtained are presented in Figures 1 and 2 and Tables 6 and 7 respectively. Table 6 lists the total forest area harvested under BAU and different carbon management scenarios at four timeframes and Figure 1 presents cumulative area harvested under different scenarios. Table 7 lists the total volume of wood products generated under BAU and different carbon management scenarios and Figure 2 shows the cumulative volume harvested under all scenarios.

Under BAU, 1.8 million acres of forest area was harvested in the short-term generating 112 million tons of timber volume in Pennsylvania. In the medium term, the total forest area harvested under this scenario increased to 5.0 million acres with the volume production of 315 million tons. In the medium-long term, the total forest area harvested under BAU was 8.4 million acres with the volume production of 533 million tons and in the long term, the area harvested totaled 12.9 million acres with the volume production of 834 million tons.

Across different carbon management scenarios, in the short term, the total forest area harvested ranged from a high of 2.0 million acres in timber stand improvement (8.3% higher than the area harvested in BAU scenario) to a low of 0.3 million acres under no harvest scenario followed by 1.5 million acres under portfolio (18% lower than the area harvested in BAU for the same period), and 1.7 million acres under extended rotation scenario (11% lower than the area harvested in BAU for the same period). All other scenarios except reduced deforestation, extended rotation, portfolio, and no harvest had more area harvested compared to BAU in the short term (Table 6). In the medium term, the total forest area harvested was the highest for extended rotation scenario at 5.5 million acres (9.8% more than in BAU) followed by TSI and reduced diameter limit cut scenarios respectively. The lowest forest area in the medium term was harvested under no harvest scenario (0.7 million acres) followed by portfolio scenario (4.5 million acres). Compared to BAU, less forest area was harvested under no harvest, portfolio, reduced deforestation, restocking, controlled deer browse, afforestation 2050, and scaled up afforestation until 2030 scenarios in the medium term.

In both medium-long-term and long-term scenarios, the total forest area harvested were the highest for extended rotation scenario followed by TSI and reduced diameter limit cut scenarios respectively in the medium long term and reduced DLC and TSI scenarios respectively in the long term. The lowest forest area under both medium long term and long-term time frames were harvested under no harvest scenario followed by portfolio, reduced deforestation, restocking and controlled deer browse scenarios respectively (Table 6). The area harvested under these five scenarios were less than that under BAU in both medium long term and long-term time frames.

Compared to BAU, the total forest area harvested under extended rotation scenario declined initially (for the short term) but increased after that for all other periods considered. No harvest, reduced deforestation, and portfolio scenarios consistently harvested less forest area compared to BAU at all periods considered.

In terms of the volume harvested, in the short term, the highest volume was harvested under TSI scenario at 117 million tons (5% more than that produced under BAU scenario) followed by controlled deer browse and afforestation 2050 respectively (Table 7). In the same time frame, the lowest volume was harvested under no harvest scenario (39 million tons, which is 65% less than that under BAU) followed by portfolio (at 92 million tons) and extended rotation scenarios (at 96 million tons) respectively (Table 7). Other scenarios that resulted in lower volume harvested compared to the BAU in the short term include reduced deforestation, scaled up afforestation till 2050, and restocking. In the medium and medium-long term timeframes, the total volume harvested was the highest for TSI scenario followed by afforestation 2030 and reduced diameter limit cut scenarios respectively in the medium term and reduced DLC followed by afforestation 2030 scenarios respectively in the medium long term. The lowest volume harvested for both medium and medium-long term time frames were under no harvest followed by portfolio and extended rotation scenarios respectively. In the medium term, lower volumes compared to BAU scenario were harvested under no harvest, portfolio, extended rotation, reduced deforestation, and afforestation scaleup 2050 scenarios. In the medium long term, the same scenarios as medium term resulted in lower volumes harvested compared to BAU with an addition of two other scenarios, restocking and afforestation scaled up until 2030 which also yielded lower volumes compared to BAU in the medium long term.

In the long term, the highest volume harvested was under reduced diameter limit cut scenario (889 million tons i.e. 6.6% more than BAU scenario under the same time frame) followed by TSI and Silvopasture respectively and the lowest volume was harvested under no harvest scenario (254 million tons) followed by portfolio, reduced deforestation and extended rotation scenarios respectively (Table 7). Apart from the reduced DLC and TSI, other scenarios that yielded higher volume compared to BAU in the long term include Silvopasture, controlled deer browse, afforestation 2030, and scaled up afforestation until 2050.

Table 6. Total forest area undergoing harvest (in thousand acres) under business-as-usual and alternative carbon management scenarios in Pennsylvania at four different time frames.

Scenarios	Harvested forest area (in thousand acres) at the specified timeframe			
	2023 to 2032	2023 to 2050	2023 to 2070	2023 to 2100
Baseline	1,845	5,033	8,388	12,916
Extended Rotation	1,650	5,526	9,844	16,266
afGGRA2030	1,853	5,033	8,453	12,961
afGGRA2050	1,850	5,030	8,436	12,999
afSU2030	1,851	5,032	8,438	13,014
afSU2050	1,846	5,043	8,453	13,234
Restock	1,852	5,025	8,367	12,813
TSI	1,998	5,451	9,105	14,083
Reduced Def	1,797	4,892	8,212	12,602
Reduced DLC	1,856	5,156	8,866	15,457
Control DB	1,849	5,026	8,381	12,846
Silvopasture	1,851	5,039	8,501	13,333
Portfolio	1,510	4,519	7,828	12,332
No Harvest	258	723	1,239	1,975

afGGRA2030 = Increasing afforestation (+2376 acres/year till 2030)
afGGRA2050 = Increasing afforestation (+2376 acres/year till 2050)
afSU2030 = Increasing afforestation scale up (+23760 acres/year till 2030)
afSU2050 = Increasing afforestation scale up (+23760 acres/year till 2050)

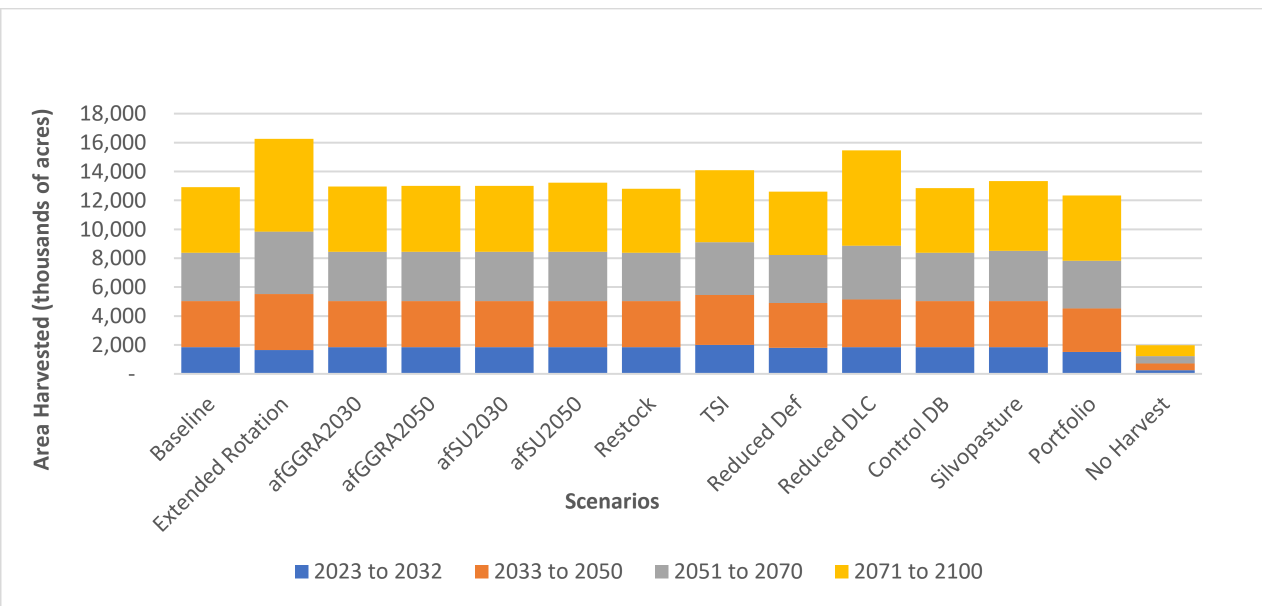


Figure 1 . Cumulative area of forest undergoing harvest treatment under business-as-usual and alternative management scenarios in Pennsylvania at four different time frames

Table 7. Volume of timber products harvested (in Million tons-US) under business-as-usual and alternative carbon management scenarios in Pennsylvania at four different timeframes.

Scenarios	Harvested timber volume (in million tons) at the specified timeframe			
	2023 to 2032	2023 to 2050	2023 to 2070	2023 to 2100
Baseline	112	315	533	834
Extended Rotation	96	290	510	825
afGGRA2030	113	320	538	836
afGGRA2050	113	317	534	833
afSU2030	112	316	532	833
afSU2050	112	314	531	836
Restock	112	316	531	826
TSI	117	330	552	862
Reduced Def	109	306	513	798
Reduced DLC	113	319	544	889
Control DB	114	318	535	837
Silvopasture	113	317	536	841
Portfolio	92	274	485	777
No Harvest	39	98	159	254

afGGRA2030 = Increasing afforestation (+2376 acres/year till 2030)
afGGRA2050 = Increasing afforestation (+2376 acres/year till 2050)
afSU2030 = Increasing afforestation scale up (+23760 acres/year till 2030)
afSU2050 = Increasing afforestation scale up (+23760 acres/year till 2050)

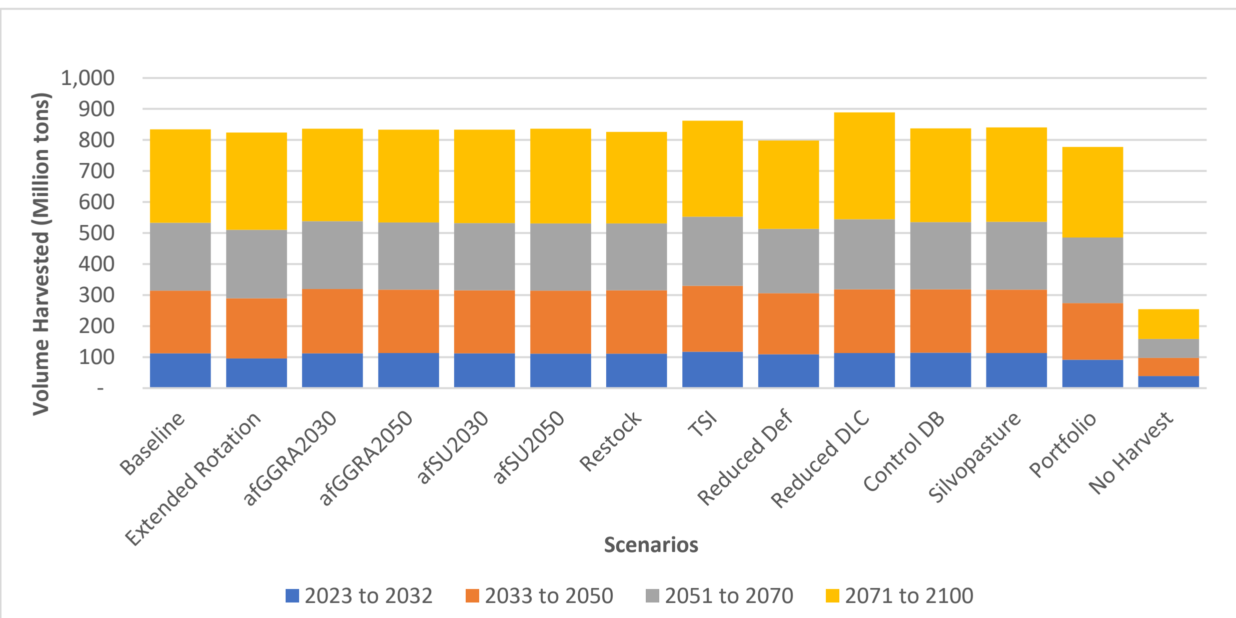


Figure 2. Cumulative volume of timber products harvested under business-as-usual and alternative management scenarios in Pennsylvania at four different time frames.

Appendix D through G show the percentage change in volume harvested under alternative carbon management scenarios compared to BAU except for no harvest scenario for four timeframes considered. Compared to BAU scenario, the total volume of timber products harvested was consistently higher during all four timeframes considered for TSI, reduced diameter limit cut, controlled deer browse, Silvopasture, and afforestation 2030 scenarios. For afforestation 2050 scenario, the volume harvested increased in the short, medium, and medium-long term in comparison to that harvested during BAU scenario but declined in the long term. Scaled up afforestation till 2030 led to an increase in volume in the short and medium term but declined after that while scaled up afforestation till 2050 led to a decline in volume harvested in the short, medium, and medium-long term but increased slightly more than BAU level in the long term. Restocking understocked forests led to a decline in volume harvested in all but medium time frame compared to the BAU scenario. Compared to BAU, the volume harvested were consistently lower in no harvest, portfolio, extended rotation, and reduced deforestation scenarios. These findings highlight that intensive afforestation and restocking of understocked forest stands do not necessarily yield higher timber volume harvested compared to BAU forest practices in Pennsylvania. Instead, forest management practices such as timber stand improvement, reduced diameter limit cut, controlling for deer browse, Silvopasture and moderate afforestation practices result in higher timber volume harvested compared to BAU in the state. The magnitude of the difference in volume harvested under portfolio and extended rotation scenarios compared to BAU decreased with increasing time frame. In the short-term, the percentage change in volume harvested under portfolio and extended rotation scenarios were 18% and 14% less than that compared to BAU respectively (Appendix D). In the long term, this change was 7% and 1% compared to BAU for portfolio and extended rotation scenarios (Appendix G). This seems logical since portfolio scenario pushes rotation age of hardwood stands by 30 years and extended rotation scenario pushes the rotation age of both hardwood and softwood stands by 30 years in Pennsylvania. The effects are therefore more prominent in short term timeframe.

Financial tradeoffs of timber products harvested under alternative management scenarios compared to BAU without considering carbon emissions using NPV criteria

The second objective of this project was to quantify the financial tradeoffs of carbon and timber products resulting from the HWPs model under different carbon management scenarios compared to BAU. For this, we estimated the total revenue and total costs associated with different carbon management scenarios including BAU as stated earlier. Next, for four different timeframes (short, medium, medium-long term and long term), we estimated the net present value obtained from forests in Pennsylvania.

The NPV generated under all carbon management scenarios considered were positive meaning that the present value of revenues obtained under each management scenario outweighed the costs incurred for implementing that scenario. Table 8 lists the NPV generated from forests in PA under different carbon management scenarios without considering the carbon emission associated with each management scenario. Figure 3 shows the cumulative NPV without considering carbon emission at four timeframes considered.

Table 8**.** Net present value estimated from Pennsylvania's forests under different carbon management scenarios including business-as-usual for four time periods without considering carbon leakage.

Scenarios	Net Present Value (NPV) in million dollars			
	2023 to 2032	2023 to 2050	2023 to 2070	2023 to 2100
Baseline	2,087	4,954	7,122	9,020
Extended Rotation	1,732	4,471	6,693	8,665
afGGRA2030	2,088	5,014	7,186	9,065
afGGRA2050	2,099	4,955	7,117	8,998
afSU2030	1,963	4,832	6,982	8,882
afSU2050	1,923	4,597	6,752	8,676
Restock	2,062	4,916	7,041	8,893
TSI	2,157	5,097	7,274	9,207
Reduced Def	2,034	4,787	6,843	8,635
Reduced DLC	2,110	5,001	7,232	9,364
Control DB	2,140	5,011	7,173	9,083
Silvopasture	2,095	4,954	7,117	9,022
Portfolio	1,526	3,981	6,026	7,818
No Harvest	601	1,421	2,067	2,690

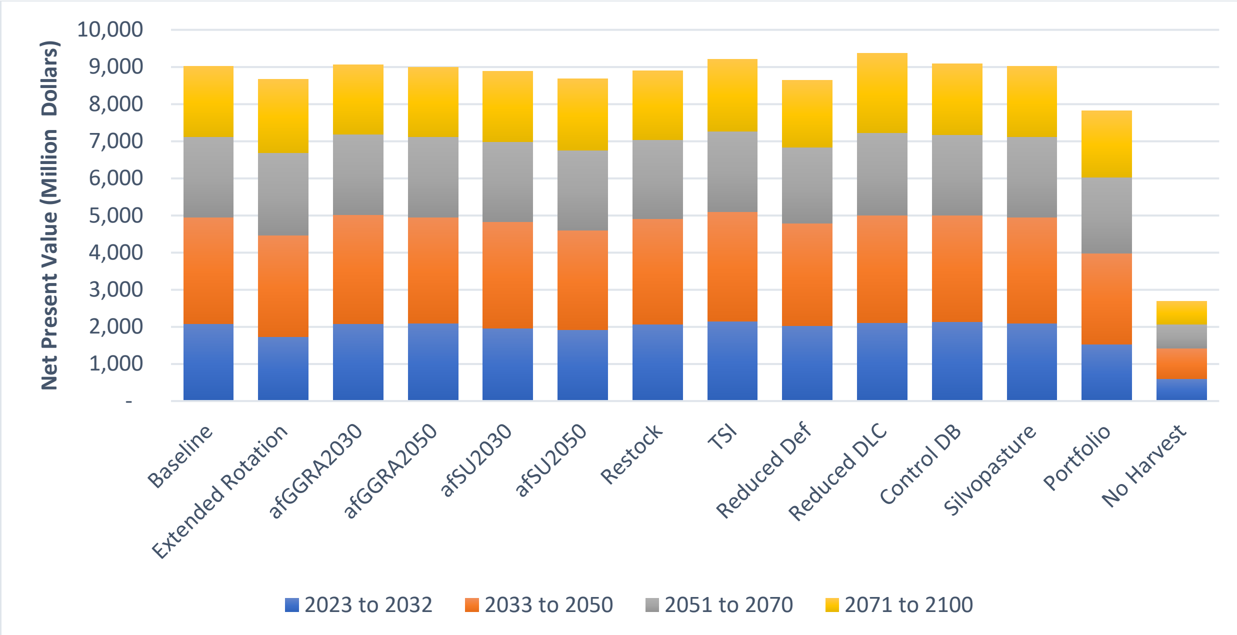


Figure 3. Cumulative net present value estimated from Pennsylvania's forests under various carbon management scenarios without considering carbon emissions at four timeframes.

The NPV generated under BAU scenario was $ 2,087 million in the short-term time frame (2023 to 2032). It increased to reach $ 4,954 million in the medium term (2023 to 2050), $ 7,122 million in the medium-long term (2023 to 2070) and $ 9,020 million in the long term (2023 to 2100).

In the short-term, the NPV generated under various carbon management scenarios ranged from a high of $2,157 million under TSI scenario (which is 3.3% more than that under BAU scenario) to a low of $601 million dollars under no harvest scenario (which is 71% less than that under BAU scenario). Apart from TSI scenario, other management scenarios that yield higher NPV compared to BAU in the short term include controlled deer browsing, reduced diameter limit cut, afforestation 2050, Silvopasture, and afforestation 2030. Portfolio scenario yielded 27% lower NPV compared to BAU and Extended rotation yielded 17% lower NPV compared to BAU in the short term (Table 8).

In the medium term, medium-long term and long term, the net present value resulting from four alternative management scenarios (TSI, reduced diameter limit cut, increasing afforestation till 2030, and controlled deer browse) were consistently higher than that obtained under BAU. No harvest scenario followed by portfolio and extended rotation scenarios yielded the lowest NPV during short, medium and medium-long term time frames. In the long term, the NPV generated under no harvest scenario was the lowest followed by portfolio, reduced deforestation and extended rotation scenarios respectively. Both cases of scaled up afforestation scenarios, restocking, and reduced deforestation consistently yielded lower NPV compared to BAU at all time frames considered. Appendix H through K show percentage change in NPV under different carbon management scenarios compared to BAU without considering carbon emissions at four timeframes considered.

Though volume harvested under five scenarios (TSI, reduced diameter limit cut, control deer browse, silvopasture, and afforestation 2030) were consistently higher than that under BAU in Pennsylvania at all time frames considered, the NPV was consistently higher than BAU in four out of the five scenarios. These included TSI, reduced DLC, controlled deer browsing, and afforestation until 2030 scenarios. Silvopasture yielded higher NPV than BAU in the short, medium, and long term but not in the medium long term.

Financial tradeoffs of timber products harvested under alternative management scenarios compared to BAU while taking into consideration carbon emissions associated with each carbon management scenario.

Next, we re-estimated the NPV considering carbon emissions associated with each alternative carbon management scenarios under emission 64 (Table 9) and emission 84 (Table 10) leakage factors. Figures 4 and 5 show the cumulative NPV with carbon under emission 64 and emission 84 leakage factors at four timeframes considered.

Compared to the NPV estimated without considering carbon emissions, the NPV with carbon (under emission 64 leakage factor) was higher in case of all other scenarios except no harvest and TSI. When carbon emission under emission 64 leakage factor were taken into consideration while estimating the NPV, the NPV generated under six different forest management scenarios (Silvopasture, controlled deer browse, reduced DLC, TSI, afforestation until 2050 and 2030) were consistently higher than that under BAU at all time frames considered. NPV with carbon under no harvest, portfolio, extended rotation, both cases of scaled up afforestation, restocking and reduced deforestation were consistently lower than that under BAU at time frames considered. The NPV with carbon was the highest under controlled deer browse followed by silvopasture in the short term. In the long term, the NPV was the highest under reduced DLC scenario followed by silvopasture. In all time frames considered, the NPV with carbon was the lowest under no harvest scenario followed by the portfolio and extended rotation scenarios in the short, medium and medium-long term, and portfolio and reduced deforestation in the long term. Though NPV under TSI scenario decreased when carbon emissions were taken into account, it was still higher than the NPV under BAU at all time frames considered. Two scenarios (afforestation until 2050 and silvopasture) that had lower NPV compared to BAU when carbon emission was not accounted for had higher NPV than BAU when carbon emissions were taken into consideration while estimating NPV under emission 64 leakage factor.

When carbon emissions under emission 84 leakage factor were accounted for while estimating the NPV, the NPV generated under most of the alternative management scenarios increased except for TSI and no harvest scenarios. The NPV with carbon under TSI was lower than the NPV without carbon at all time frames considered while NPV with carbon under no harvest was lower than the NPV without carbon only in the short term.

The NPV with carbon under emission 84 leakage factor were consistently higher than the NPV under BAU for six forest management scenarios (Silvopasture, controlled deer browse, reduced DLC, TSI, afforestation until 2050 and restocking) and lower than the NPV under BAU for four scenarios (No harvest, portfolio, extended rotation, and reduced deforestation). The NPV with carbon (under emission 84 leakage factor) was the highest under controlled deer browse followed by silvopasture in the short term, and reduced DLC followed by silvopasture in the long term. The lowest NPV with carbon was noted under no harvest followed by portfolio and extended rotation at all time frames considered.

Though NPV under TSI scenario declined when carbon emission under emission 84 leakage factor was considered, it still exceeded NPV generated under BAU at all time frames considered. Three scenarios that had lower NPV compared to BAU when carbon emission was not accounted for had higher NPV than BAU when carbon emissions were taken into consideration while estimating NPV under emission 84 leakage factor. These include afforestation until 2050, restocking and silvopasture scenarios.

Table 9. Net present value estimated from Pennsylvania's forests under business-as-usual and alternative management scenarios while accounting for carbon emissions using emission 64 leakage factor.

Scenarios	Net Present Value (NPV) in million dollars			
	2023 to 2032	2023 to 2050	2023 to 2070	2023 to 2100
Baseline	$ 2,087	$ 4,954	$ 7,122	$ 9,020
Extended Rotation	$ 1,745	$ 4,523	$ 6,745	$ 8,711
afGGRA2030	$ 2,098	$ 5,026	$ 7,198	$ 9,078
afGGRA2050	$ 2,110	$ 4,975	$ 7,140	$ 9,023
afSU2030	$ 2,022	$ 4,911	$ 7,072	$ 8,976
afSU2050	$ 1,990	$ 4,775	$ 6,976	$ 8,922
Restock	$ 2,065	$ 4,925	$ 7,056	$ 8,914
TSI	$ 2,139	$ 5,027	$ 7,161	$ 9,067
Reduced Def	$ 2,035	$ 4,794	$ 6,853	$ 8,646
Reduced DLC	$ 2,110	$ 5,003	$ 7,261	$ 9,452
Control DB	$ 2,153	$ 5,055	$ 7,247	$ 9,189
Silvopasture	$ 2,152	$ 5,089	$ 7,311	$ 9,255
Portfolio	$ 1,601	$ 4,220	$ 6,386	$ 8,298
No Harvest	$ 557	$ 1,400	$ 2,043	$ 2,629

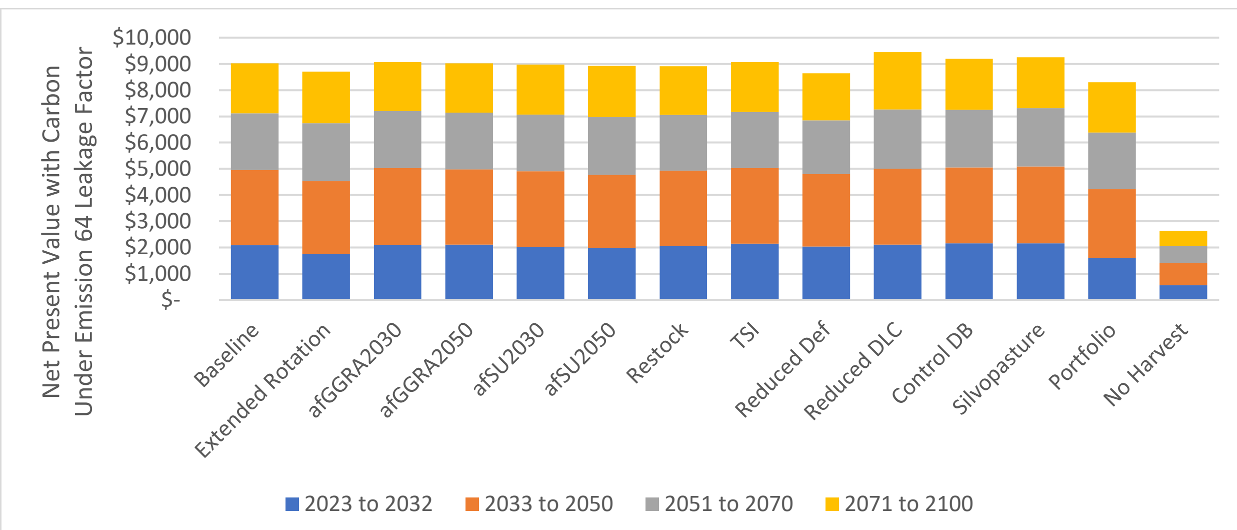


Figure 4. Cumulative net present value estimated from Pennsylvania's forests under various carbon management scenarios considering carbon emissions under emission 64 leakage factor.

Table 10. Net present value estimated from Pennsylvania's forests under business-as-usual and alternative management scenarios while accounting for carbon emissions using emission 84 leakage factor.

Scenarios	Net Present Value (NPV) in million dollars			
	2023 to 2032	2023 to 2050	2023 to 2070	2023 to 2100
Baseline	$ 2,087	$ 4,954	$ 7,122	$ 9,020
Extended Rotation	$ 1,749	$ 4,524	$ 6,744	$ 8,711
afGGRA2030	$ 2,073	$ 5,029	$ 7,236	$ 9,177
afGGRA2050	$ 2,162	$ 5,093	$ 7,304	$ 9,225
afSU2030	$ 2,073	$ 5,029	$ 7,236	$ 9,177
afSU2050	$ 2,040	$ 4,892	$ 7,139	$ 9,123
Restock	$ 2,116	$ 5,042	$ 7,219	$ 9,115
TSI	$ 2,139	$ 5,027	$ 7,162	$ 9,067
Reduced Def	$ 2,086	$ 4,909	$ 7,012	$ 8,841
Reduced DLC	$ 2,162	$ 5,121	$ 7,425	$ 9,656
Control DB	$ 2,204	$ 5,173	$ 7,412	$ 9,392
Silvopasture	$ 2,203	$ 5,207	$ 7,475	$ 9,457
Portfolio	$ 1,607	$ 4,225	$ 6,389	$ 8,299
No Harvest	$ 595	$ 1,467	$ 2,118	$ 2,705

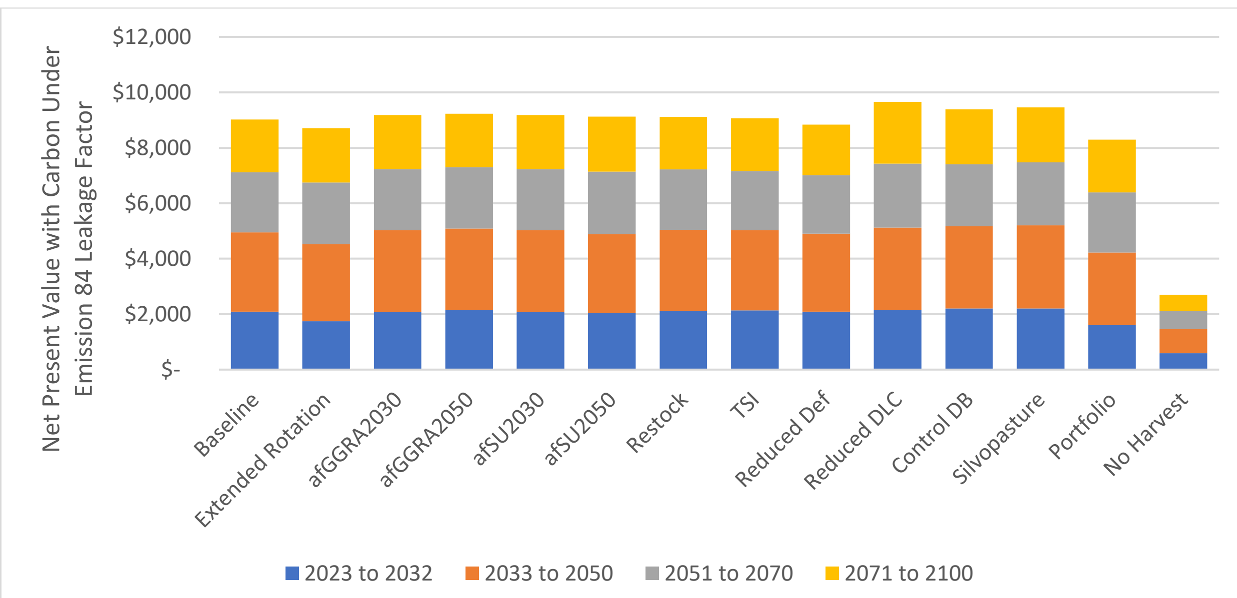


Figure 5. Cumulative net present value estimated from Pennsylvania's forests under various carbon management scenarios considering carbon emissions under emission 84 leakage factor.

Figures 6 through 9 show NPV with and without considering carbon emissions under short, medium, medium-long, and long-term timeframes respectively.

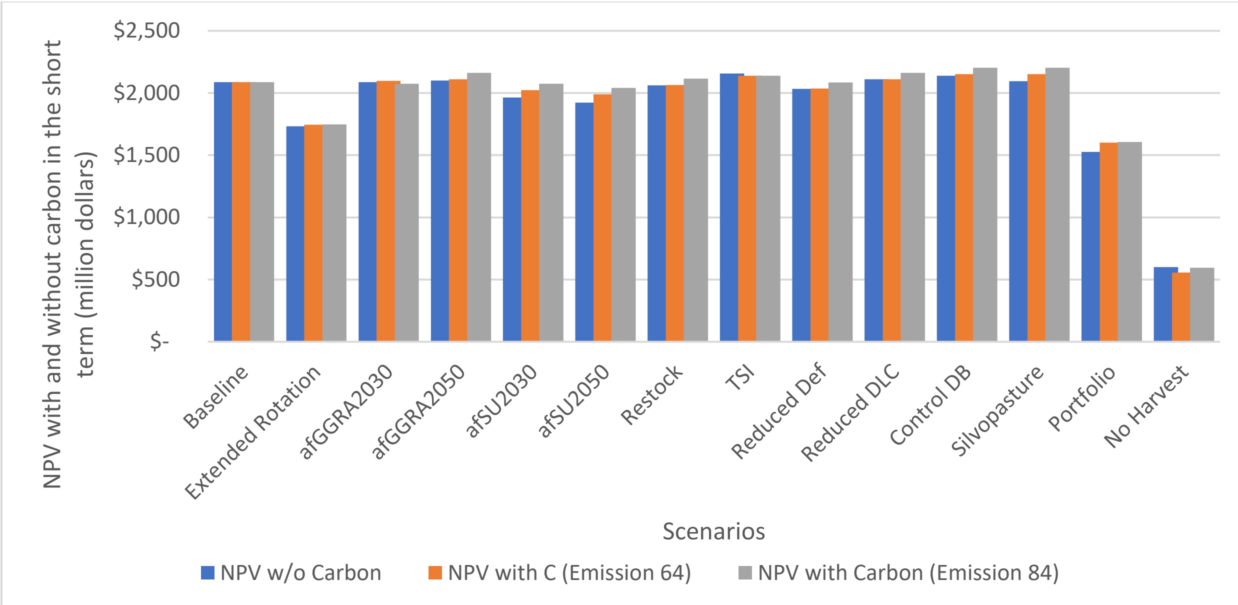


Figure 6. Net present value estimated with and without accounting for carbon emissions under various carbon management scenarios in the short-term time frame (2023 to 2032).

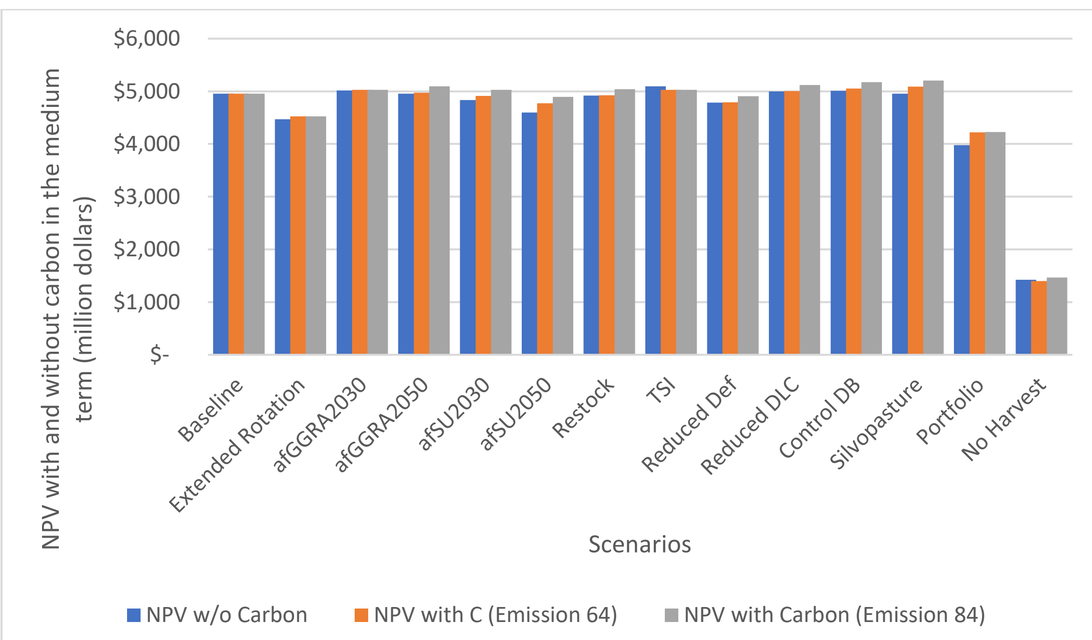


Figure 7. Net present value estimated with and without accounting for carbon emissions under various carbon management scenarios in the medium-term time frame (2023 to 2050).

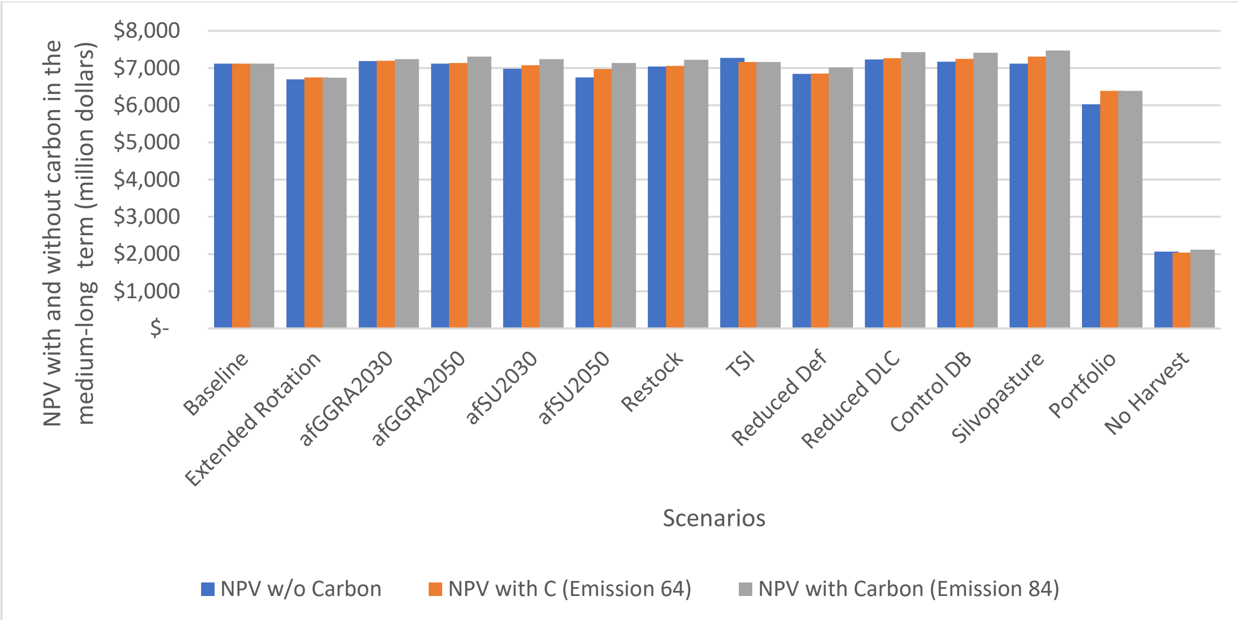


Figure 8. Net present value estimated with and without accounting for carbon emissions under various carbon management scenarios in the medium-long term time frame (2023 to 2070).

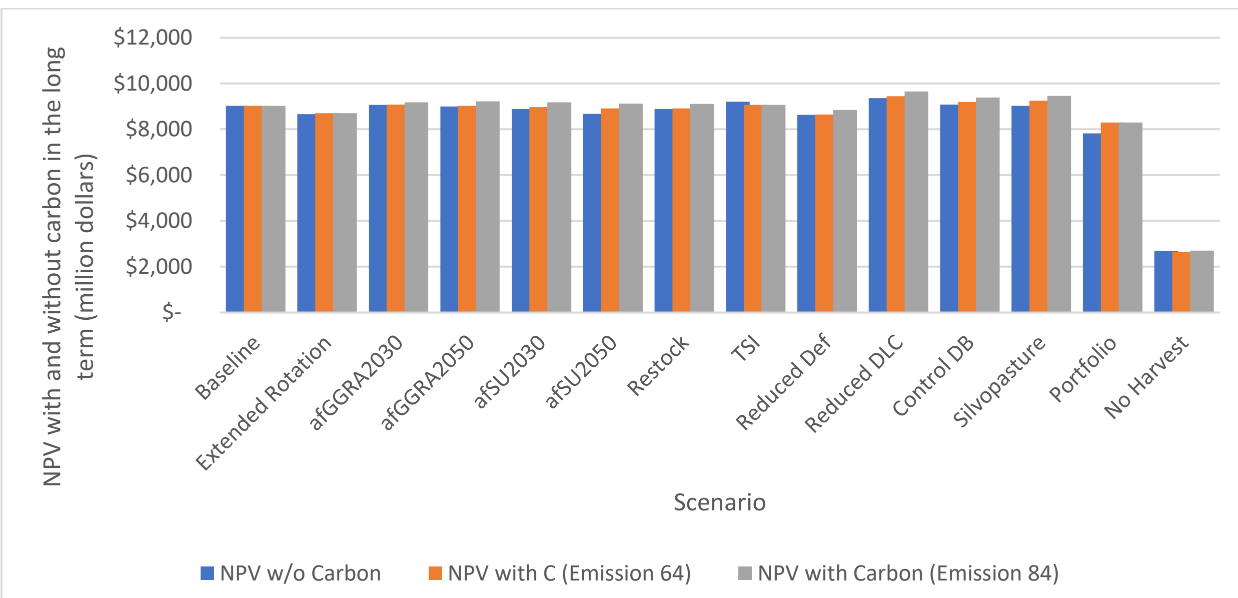


Figure 9. Net present value estimated with and without accounting for carbon emissions under various carbon management scenarios in the long-term time frame (2023 to 2100).

Sensitivity Analysis

Sensitivity analysis was conducted using a range of discount rates (3% to 15%), carbon prices ($5 to $100) and timber prices (both increase and decrease) to assess how NPV under different carbon management scenarios reacted to changing parameters. The results obtained are presented in figures 10 through 14. Figure 10 depicts the change in NPV when interest rate is increased from 3% to 15%. It can be noted that as interest rate increases, NPV decreases. This is because as the interest rate increases, the present value of future revenue decreases since higher interest rate implies greater discounting of future cash flows. The rate of decline in NPV under different carbon management scenarios with increasing interest rate was noted to be constant. This is because the HWPs model (which is an ecological model) does not consider market variables when predicting timber harvests. Timber harvest volumes in the HWPs model do not change with changing interest rate. A market-based model for predicting timber harvests could provide a more realistic estimation of how volume harvested changes with changing interest rates.

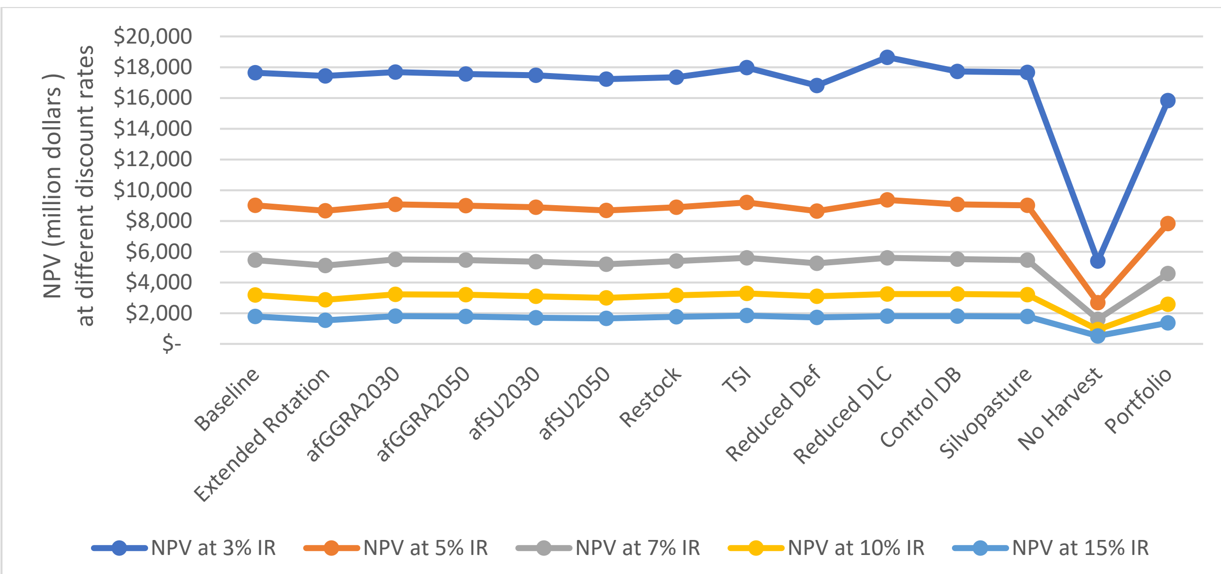


Figure 10. NPV under different carbon management scenarios at varying interest rates in Pennsylvania (2023 to 2100).

Sensitivity analysis was also conducted by changing the market price of carbon from $5 to $100, the results of which are presented in Figure 11. It can be noted that with the increase in the price of carbon, the NPV increases in all scenarios except no harvest and TSI. That is because in these two scenarios, total carbon emission under emission 64 leakage factor is positive while in all other scenarios, carbon emission is negative. Therefore, forest management scenarios other than TSI and no harvest generate revenue from carbon sequestration and so the NPV for these other scenarios increases with increase in carbon price. Scenarios such as portfolio, extended rotation and scaled up afforestation which generate lower NPV compared to BAU at the market price of carbon also generate NPV higher than BAU when the price of carbon is increased as shown in figure 11. On the other hand, the NPV under TSI scenario is higher than the NPV under BAU at the market price of carbon, however, as the price of carbon continues to increase, the NPV under TSI declines below the NPV under BAU.

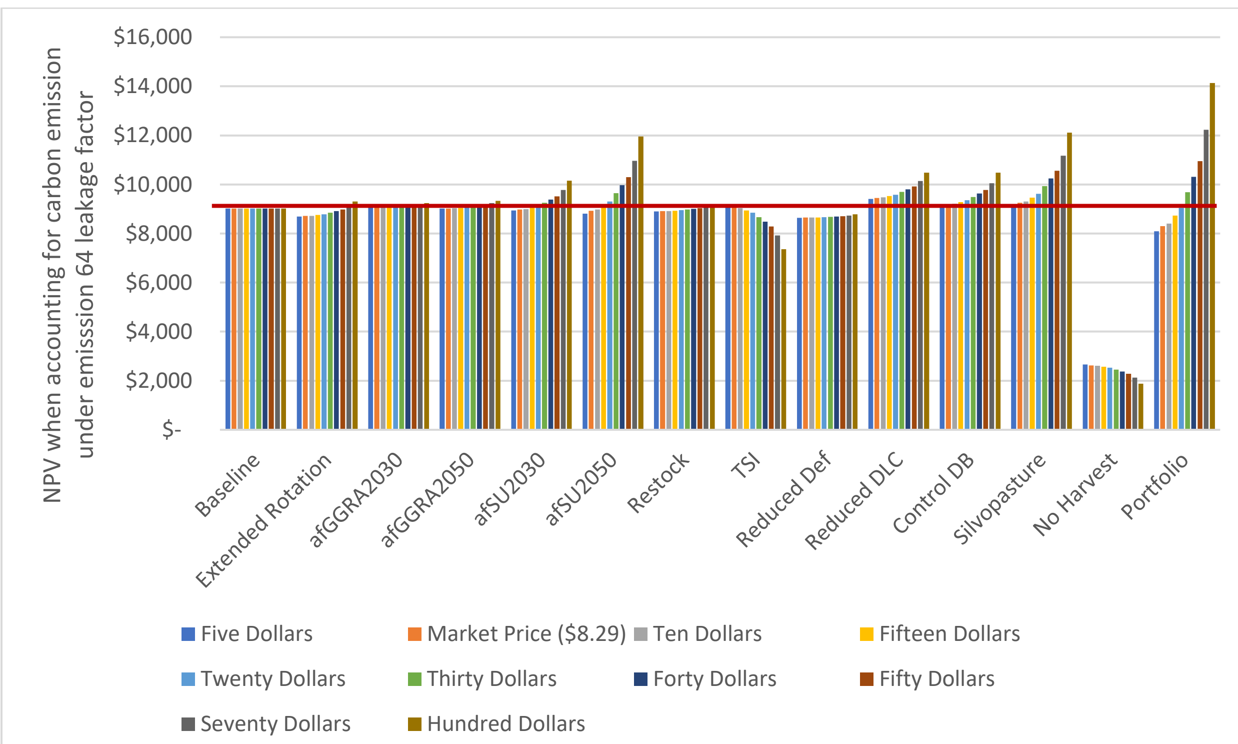


Figure 11. NPV under different carbon management scenarios at varying carbon prices in the Pennsylvania (2023 to 2100)

Sensitivity analysis was also conducted to assess the change in NPV resulting from the change in stumpage prices. For this, five increasing stumpage price scenarios and five decreasing stumpage price scenarios compared to the baseline used for financial analysis were considered. In the base case scenario for Pennsylvania, the stumpage price of hardwood species was increased by 3% every year and that of softwood species by 2.5% every year. For conducting sensitivity analysis with increasing price, in addition to the base case, the stumpage price of hardwoods was increased by 1% every year till it reached 8% and for the softwoods it was increased by 0.5% every year till it reached 5%. Likewise, for conducting sensitivity analysis with decreasing price, stumpage price for both hardwoods and softwoods were decreased by 1% every year from the base case level till the stumpage price was reduced by 5 percent points for both hardwoods and softwoods. The results obtained from increasing and decreasing stumpage price analyses are presented in Figures 12 and 13 respectively. NPV increases with increasing stumpage price and decreases with decreasing stumpage price. With the increase in stumpage price, there is a considerable increase in NPV under scenarios such as reduced DLC and TSI. Other scenarios that yield higher NPV compared to BAU when stumpage price is increased include Silvopasture and extended rotation (Figure 12). When the stumpage price is decreased , afforestation 2030 and controlled deer browsing are the only scenarios that yield higher NPV compared to BAU in the long-term timeframe. Reduced DLC and TSI scenarios yield higher NPV compared to BAU at the base price used but yield less NPV compared to BAU when the stumpage price declines by one percentage point in case of reduced DLC and 2 percentage points in case of TSI.

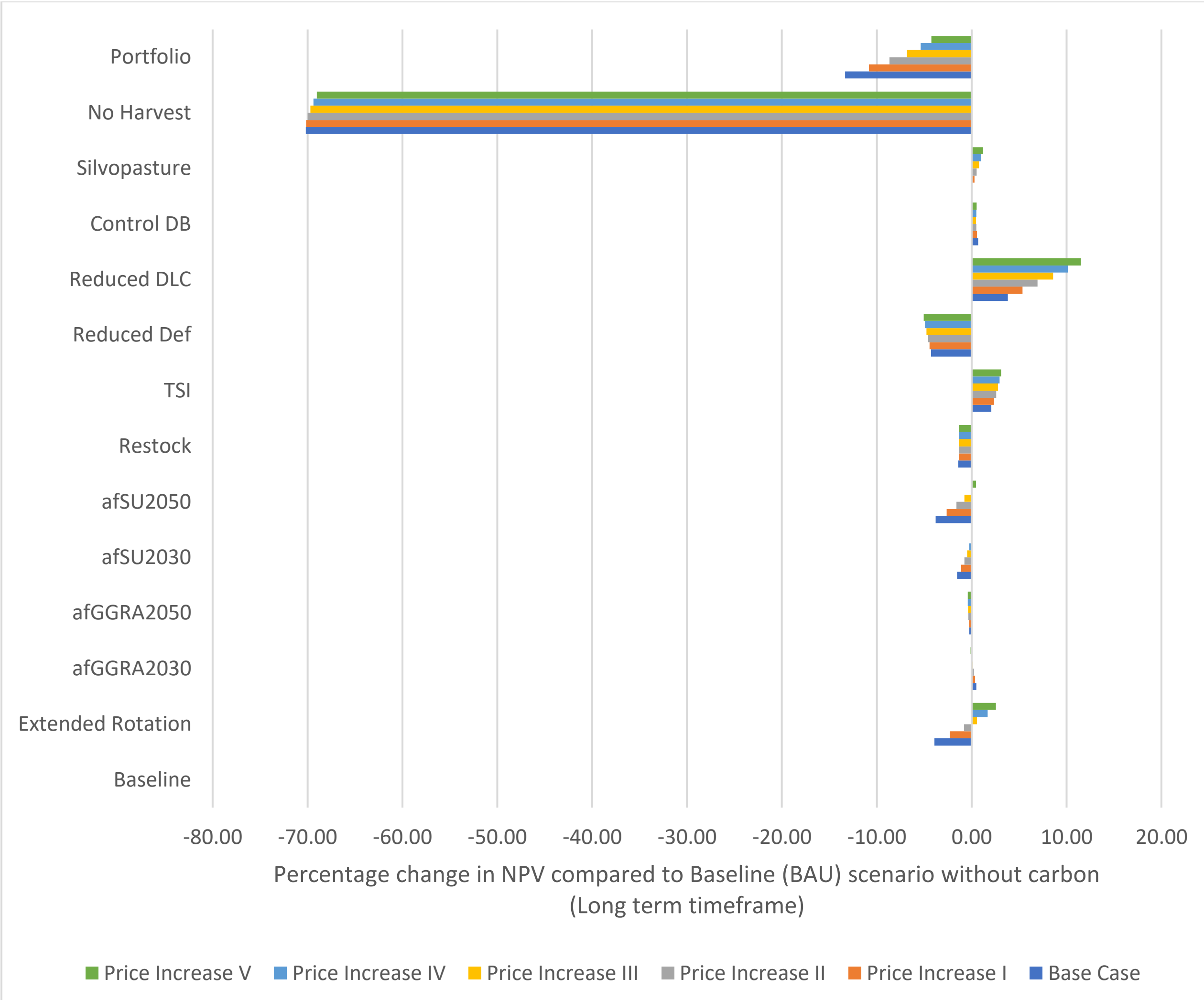


Figure 12. Percentage change in NPV under different carbon management scenarios compared to BAU scenario when stumpage price is increased in the long term.

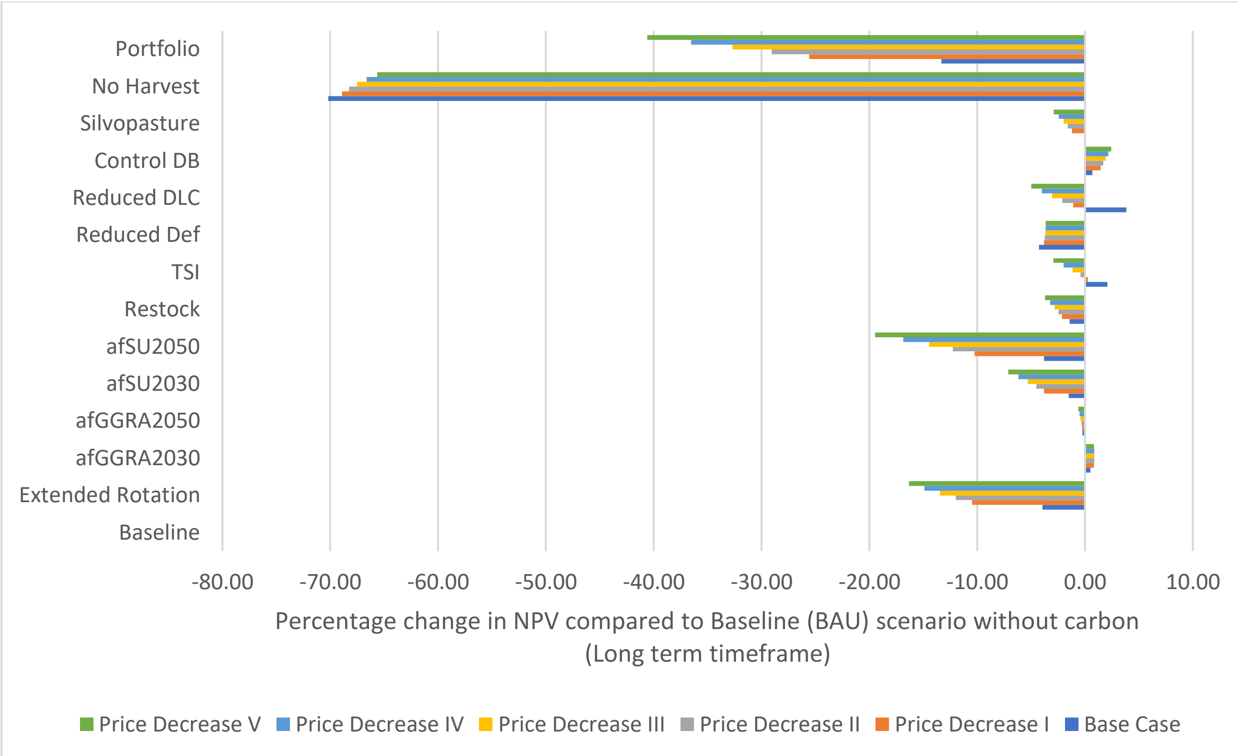


Figure 13. Percentage change in NPV under different carbon management scenarios compared to BAU scenario in Pennsylvania when stumpage price is decreased (2023 to 2100).

Key Takeaways

- NPV is positive under all scenarios considered meaning that economically all scenarios are feasible to undertake without incurring a loss in investment.
- When carbon emissions associated different forest management scenarios are not taken into consideration while estimating the NPV, four alternative management scenarios (Reduced diameter limit cut, timber stand improvement, controlled deer browsing, and afforestation until 2030) yield higher NPV compared to the NPV under business-as-usual scenario.
- When carbon emissions associated with different forest management scenarios are also accounted for when estimating NPV, six scenarios generate higher NPV compared to that generated under BAU using emission 64 leakage factor. These include silvopasture, controlled deer browsing, reduced DLC, TSI, afforestation until 2050 and 2030 scenarios.
- When carbon emissions are accounted for using emission 84 leakage factor, again six scenarios yield NPV higher than that generated under BAU. These include silvopasture, controlled deer browsing, reduced DLC, TSI, afforestation until 2050, and restocking scenarios.
- For scenarios like extended rotation, portfolio, and scaled up afforestation to yield higher NPV compared to BAU scenario, market price of carbon needs to be higher than what it is at present.

References

Bullard, S.H., and T.J. Straka. 1998. Basic Concepts in Forest Valuation and Investment Analysis. Preceda, L.L.C.

Dickens, D., D. Clabo, D. Moorhead, and C. Waldrop. 2021. Growing poles in southern pine stands. University of Georgia. Warnell school of forestry and natural resources. Publication WSFNR-21-70C. 6p.

Dickmann, D., and R. Melvin. 1997. Managing rep pine plantations for utility poles. Michigan State University. Department of Forestry Extension Bulletin E-2612. 10p.

Hoover, K., and A.A. Riddle. 2022. U.S. Forest carbon data: In brief. Congressional Research Service. R46313. Available online at: https://crsreports.congress.gov/product/pdf/R/R46313. Last accessed 11/1/2022.

Jacobson, M. 2022. Timber prices: 10-year summary of price trend percentages. Available online at: https://extension.psu.edu/timber-prices-10-year-summary-of-price-trend-percentages. Last accessed 11/1/2022.

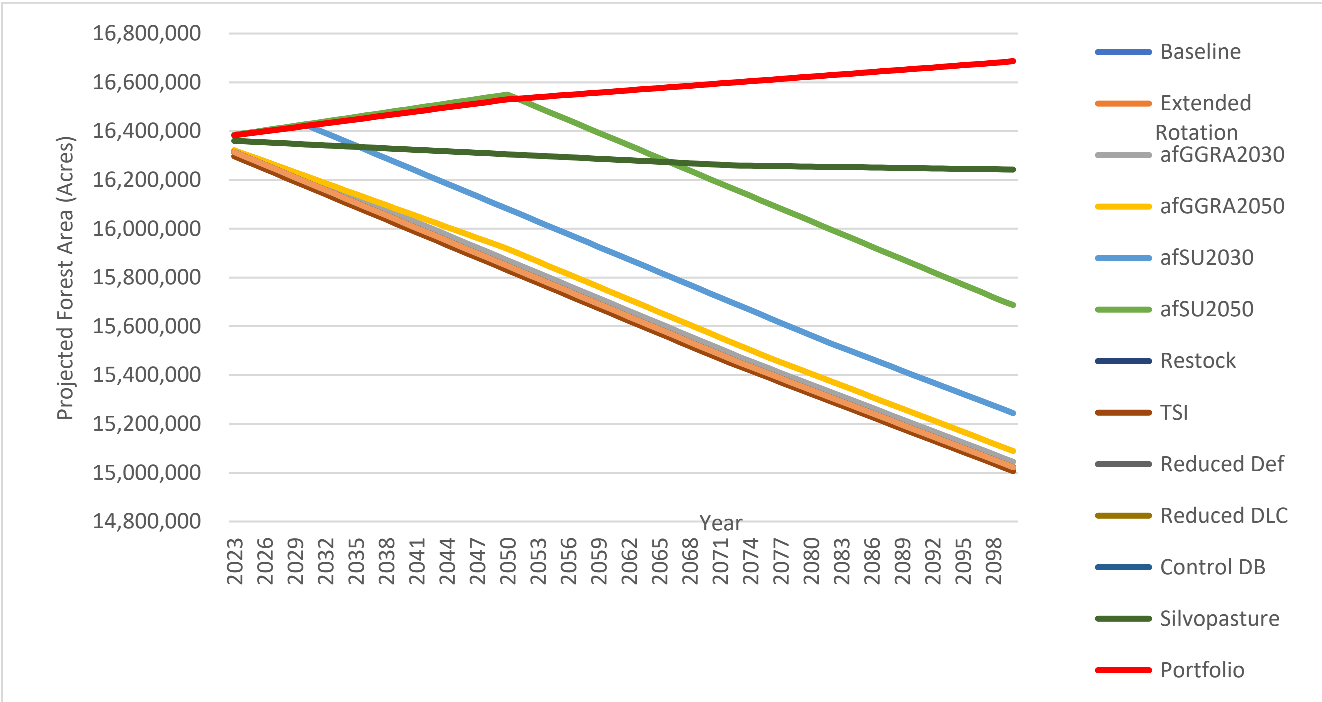
Jacobson, M. 2007. Forest Finance 2: Fencing for Forest Regeneration: Does It Pay?. Available online at: https://extension.psu.edu/forest-finance-2-fencing-for-forest-regeneration-does-it-pay#:~:text=Introduction,regenerate%20naturally%20after%20a%20harvest.. Last accessed 11/2/2022.

Smith, J.E., L.S. Health, K.E. Skog, and R.A. Birdsey. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. United States Department of Agriculture, Forest Service. General Technical Report NE- 343. 222p.

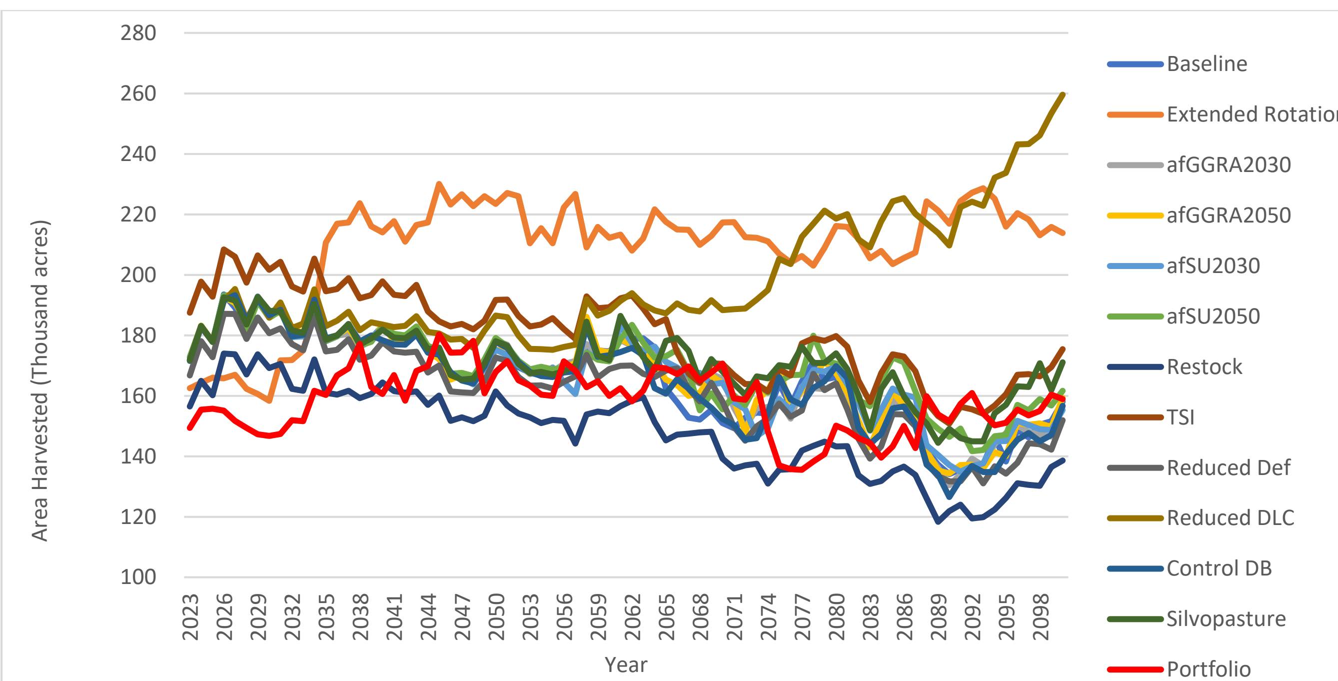
Winn, M.F., L.A. Royer., J.W. Bentley, R.J. Piva, T.A. Morgan, E.C. Berg, and J.W. Coulston. 2020. Timber products monitoring: Unit of measure conversion factors for roundwood receiving facilities. United States Department of Agriculture, Forest Service. General Technical Report SRS- 251. 154p.

Appendix

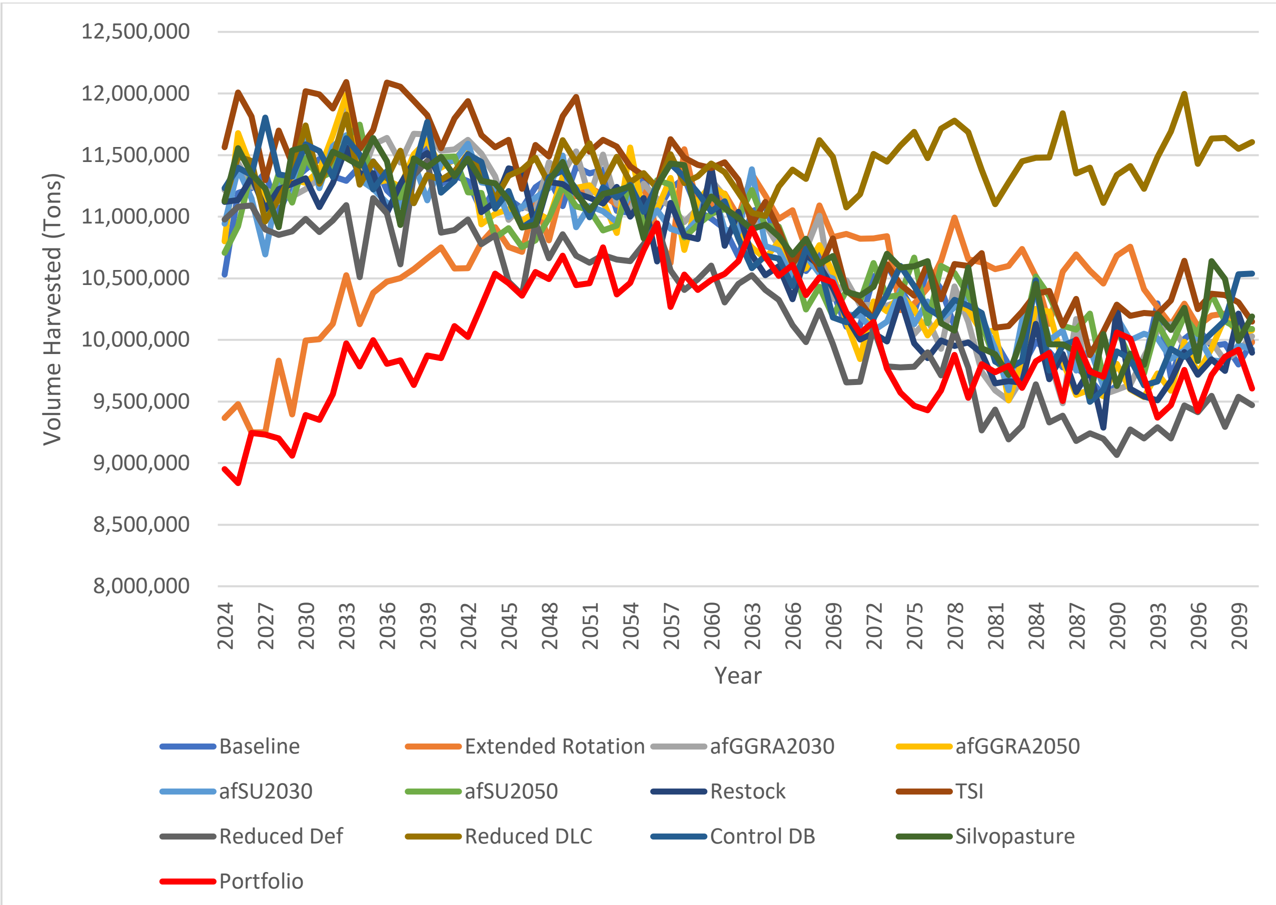
Appendix A. Projected forest area (in million acres) under BAU and alternative carbon management scenarios from year 2023 to 2100 modeled using CBM-CFS.



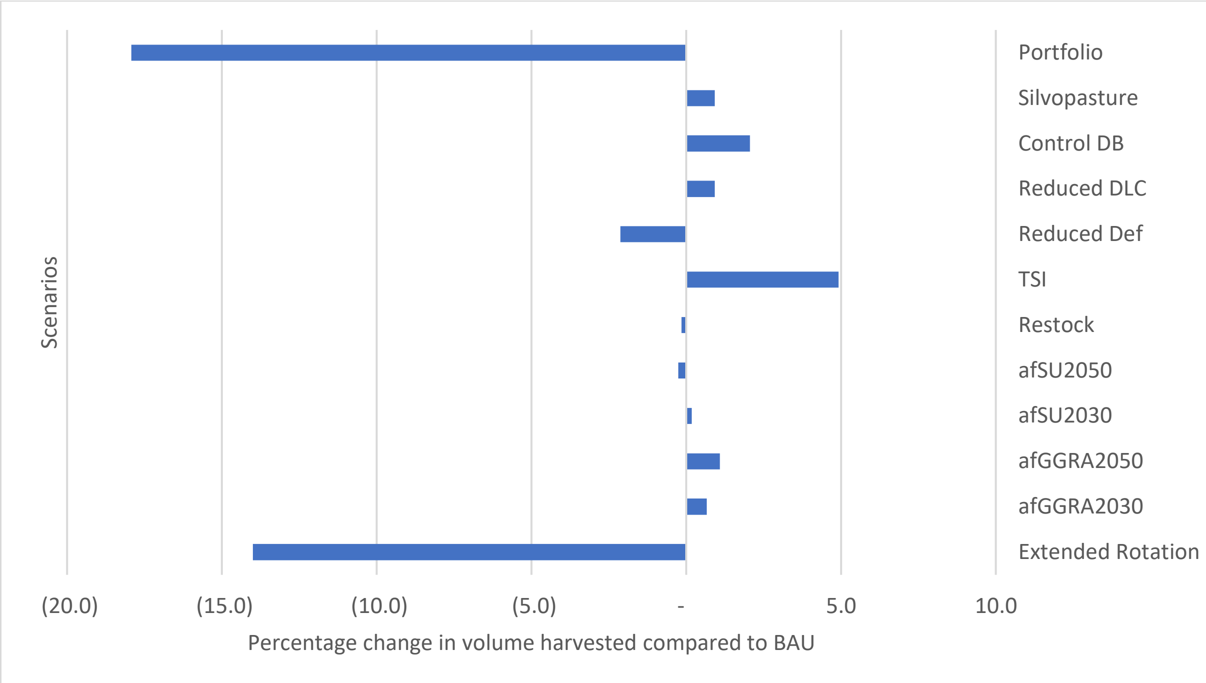
Appendix B. Forest area (in acres) harvested each year under different carbon management scenarios from the year 2023 to 2100.



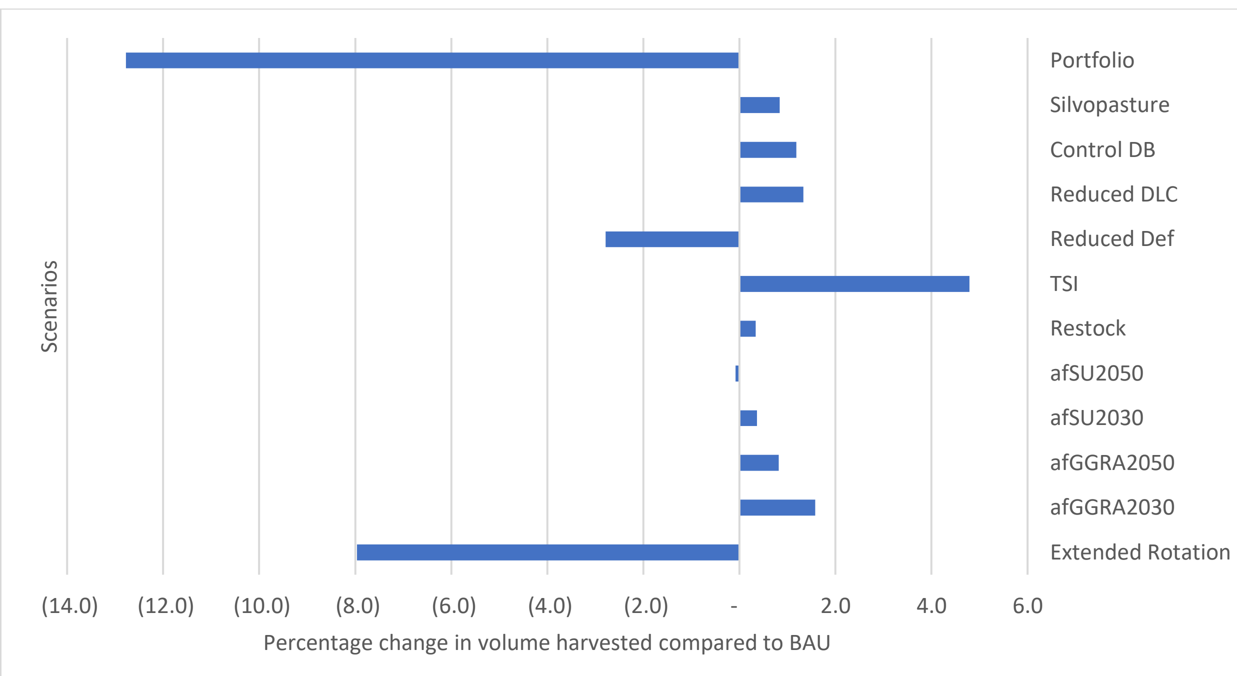
Appendix C. Volume of timber products harvested each year (in tons) under different carbon management scenarios from the year 2023 to 2100.



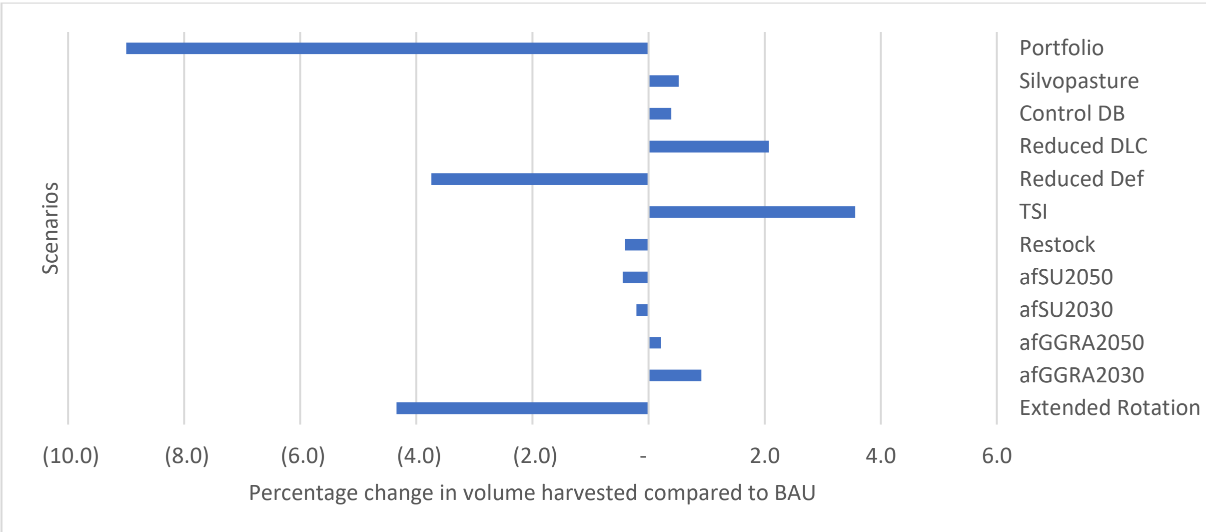
Appendix D. Percentage change in volume harvested under alternative carbon management scenarios compared to baseline for short term time frame (2023 to 2032) in Pennsylvania.



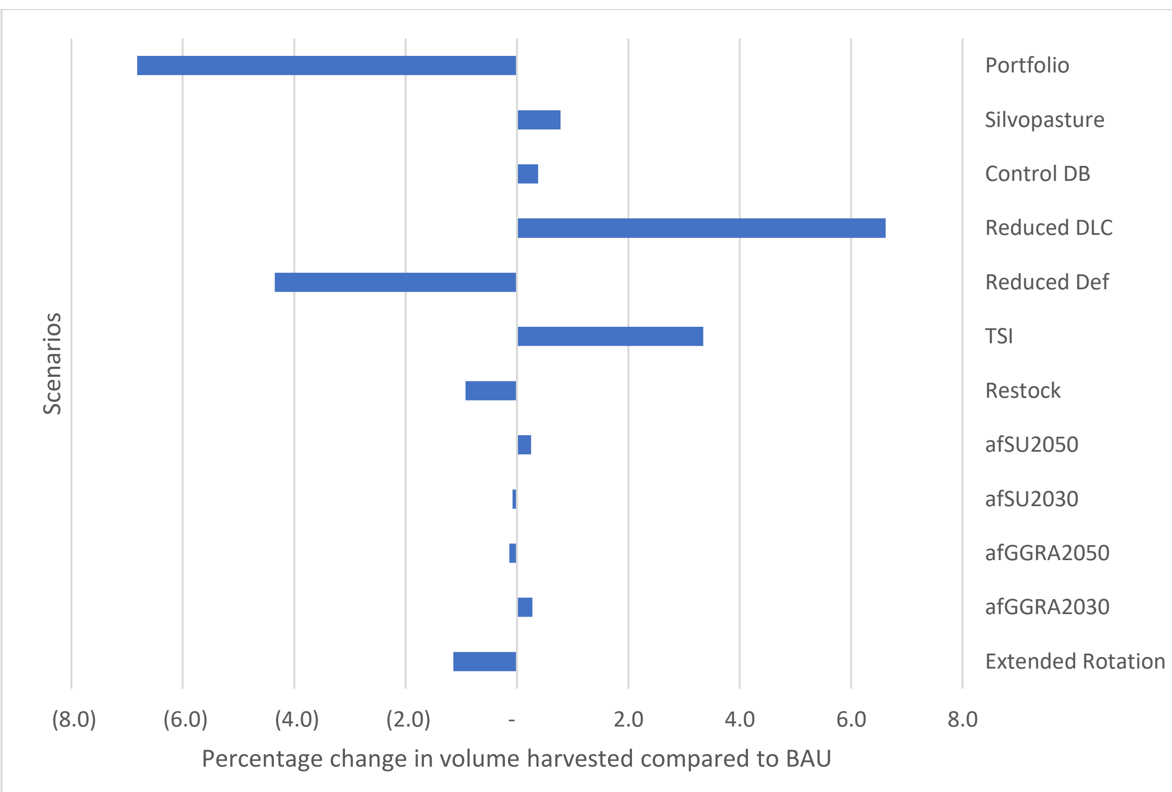
Appendix E. Percentage change in volume harvested under alternative carbon management scenarios compared to baseline for medium term time frame (2023 to 2050) in Pennsylvania.



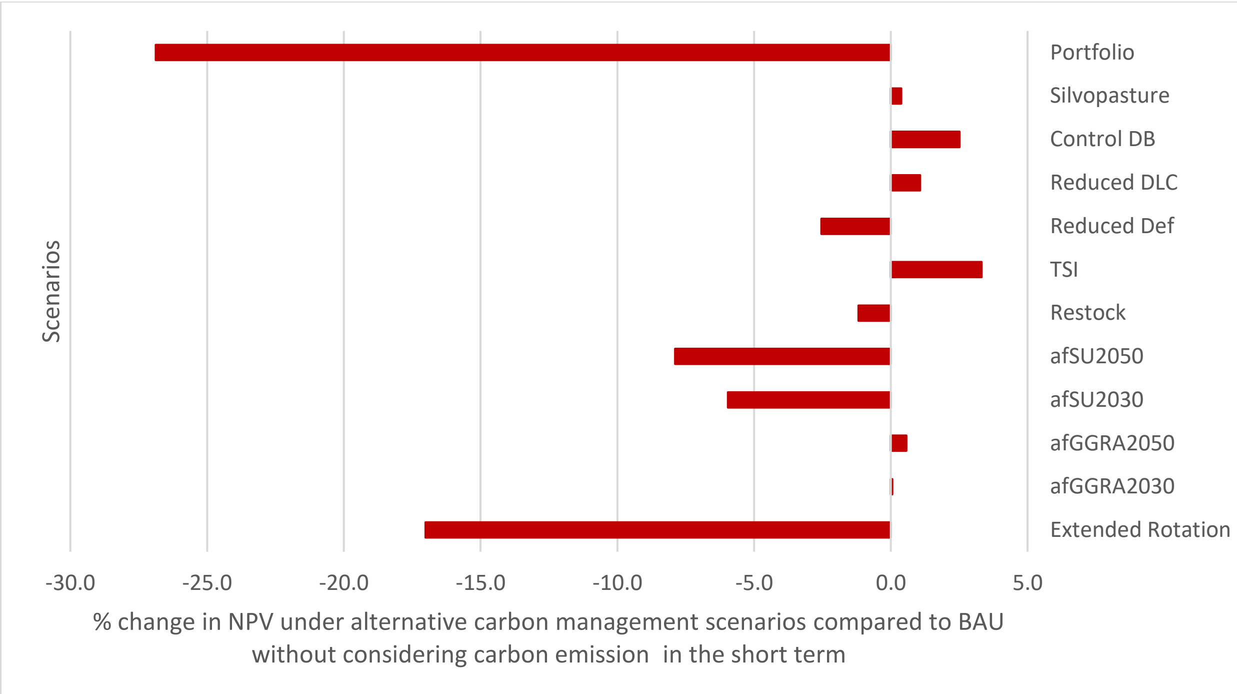
Appendix F. Percentage change in volume harvested under alternative carbon management scenarios compared to baseline for medium-long term time frame (2023 to 2070) in Pennsylvania.



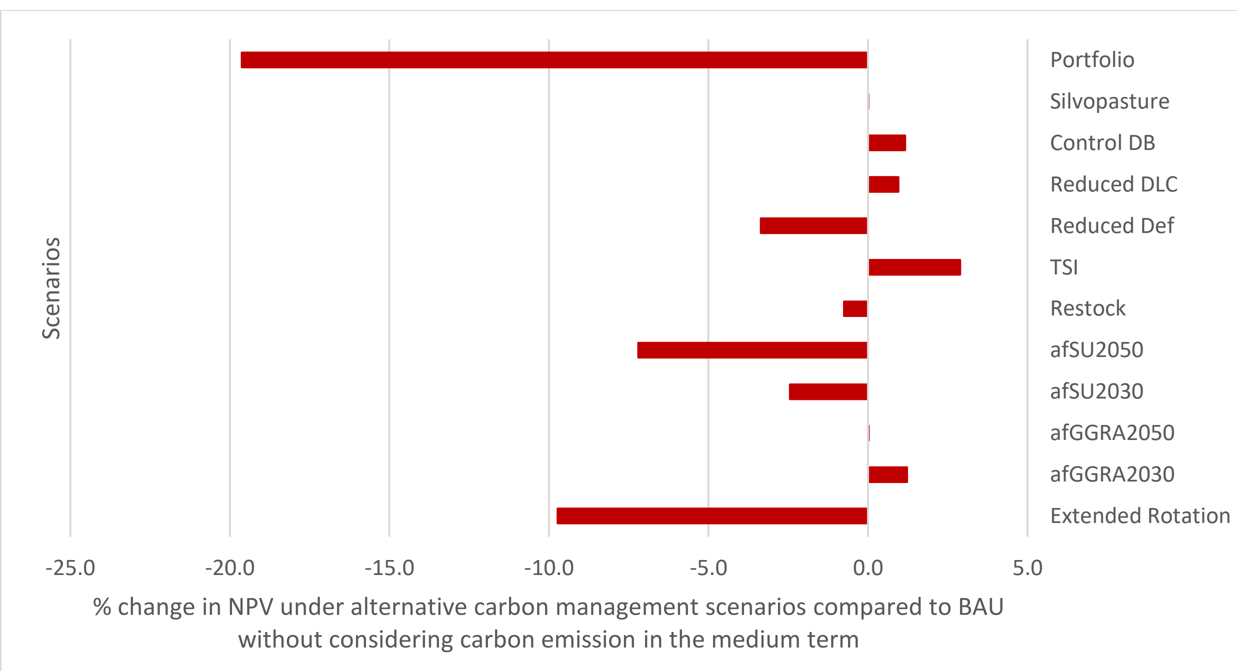
Appendix G. Percentage change in volume harvested under alternative carbon management scenarios compared to baseline for long term time frame (2023 to 2100) in Pennsylvania.



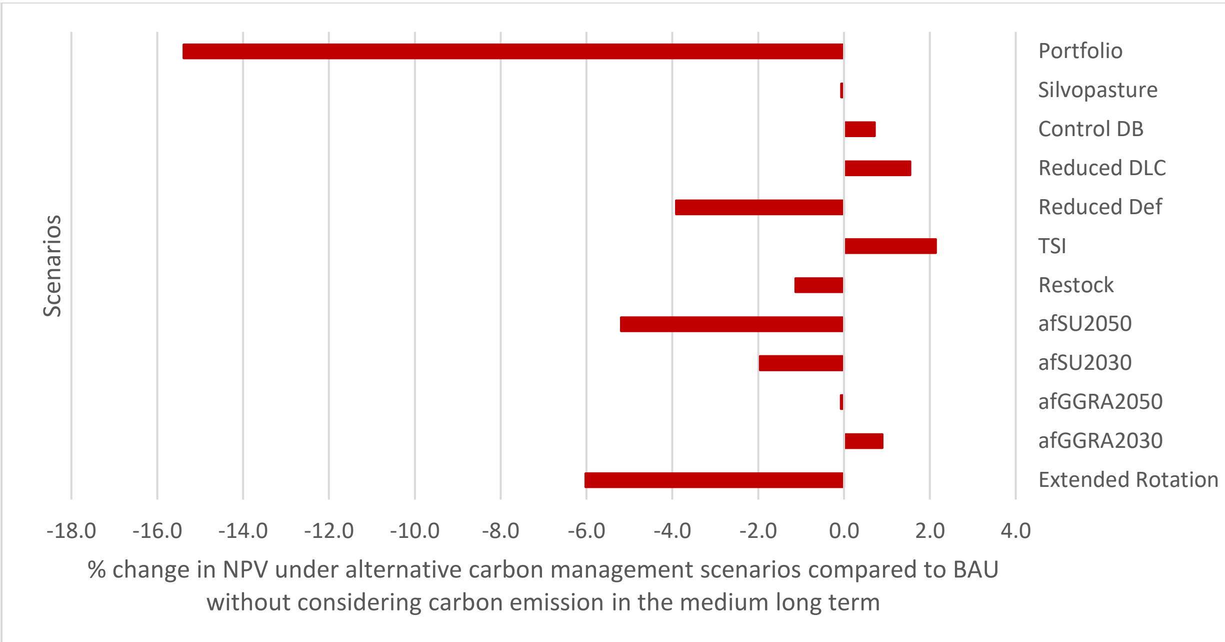
Appendix H. Percentage change in net present value (NPV) without considering carbon emission under alternative carbon management scenarios compared to business as usual for short term time frame (2023 to 2032).



Appendix I. Percentage change in net present value (NPV) without considering carbon emission under alternative carbon management scenarios compared to business as usual for medium term time frame (2023 to 2050).



Appendix J. Percentage change in net present value (NPV) without considering carbon emission under alternative carbon management scenarios compared to business as usual for medium-long term time frame (2023 to 2070).



Appendix K. Percentage change in net present value (NPV) without considering carbon emission under alternative carbon management scenarios compared to business as usual for long term time frame (2023 to 2100).