Carbon Cycling and Environmental Impacts from Growing, Harvesting, and Processing Forest Biomass in New York State

Final Report | Report Number 21-29 | November 2021

NYSERDA's Promise to New Yorkers:

NYSERDA provides resources, expertise, and objective information so New Yorkers can make confident, informed energy decisions.

Our Vision:

New York is a global climate leader building a healthier future with thriving communities; homes and businesses powered by clean energy; and economic opportunities accessible to all New Yorkers.

Our Mission:

Advance clean energy innovation and investments to combat climate change, improving the health, resiliency, and prosperity of New Yorkers and delivering benefits equitably to all.

Carbon Cycling and Environmental Impacts from Growing, Harvesting, and Processing Forest Biomass in New York State

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

Diane Bertok
Project Manager

Prepared by:

State University of New York
College of Environmental Science and Forestry

Syracuse, NY

Timothy A. Volk, Professor
Robert Malmsheimer, Professor
Diane Kiernan, Assistant Professor
Mark Eisenbies, Research Scientist
Rohit Bhonagiri, Graduate Student

NYSERDA Report 21-29 NYSERDA Contract 102959-1 November 2021

Notice

This report was prepared by the State University of New York College of Environmental Science and Forestry (SUNY ESF) in the course of performing work contracted for and sponsored by the New York State Energy Research and Development Authority (hereafter "NYSERDA"). The opinions expressed in this report do not necessarily reflect those of NYSERDA or the State of New York, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Further, NYSERDA, the State of New York, and the contractor make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods, or other information contained, described, disclosed, or referred to in this report. NYSERDA, the State of New York, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

NYSERDA makes every effort to provide accurate information about copyright owners and related matters in the reports we publish. Contractors are responsible for determining and satisfying copyright or other use restrictions regarding the content of reports that they write, in compliance with NYSERDA's policies and federal law. If you are the copyright owner and believe a NYSERDA report has not properly attributed your work to you or has used it without permission, please email print@nyserda.ny.gov

Information contained in this document, such as web page addresses, are current at the time of publication.

Preferred Citation

New York State Energy and Research Development Authority (NYSERDA). 2021. "Carbon Cycling and Environmental Impacts from Growing, Harvesting, and Processing Forest Biomass in New York State," NYSERDA Report Number 21-29. Prepared by SUNY ESF, Syracuse, NY. nyserda.ny.gov/publications

Abstract

The majority of land (63%) in New York State is covered with forests that provide a wide range of products, jobs, economic impacts, and ecosystem services, including carbon sequestration and storage. Forest management is critical to reaching the goals of the Climate Leadership and Community Protection Act (Climate Act). This study assessed how aboveground forest carbon pools change in response to management practices including (1) no management, (2) science-based “good silviculture,” and (3) poor management in the form of “high grading,” The study used a forest growth simulator developed with measurements taken from a network amounting to hundreds of forest inventory plots in NYS tracked over several decades. A base case (no forest management) and 10 other combinations of forest management using good silviculture (GS), maintaining balanced forest structure and species composition, and high grading (HG) were tested. Good silvicultural practices maintain balanced forest structure and species composition, which are key to successful and sustainable management of mixed northern hardwood stands that allows for sustained and regular yields from the stand and the provision of a range of ecosystem services. When GS is used, forest carbon stored in a single stand is typically within 90% of carbon stored in the base case (no management) scenario within 10–20 years of the harvest. GS also generates a more consistent supply of timber and other material that (1) store carbon for short (i.e., a few years for paper and packaging) and long (i.e., decades for some wood used in furniture and housing) time periods and (2) provides raw material that is essential for the forest and energy industries. When HG is practiced, the carbon stocks in the forest never return above 60% of the level in the base case over the 25 years period modeled. HG is a poor choice from both a carbon storage standpoint and in terms of providing a consistent and sustainable supply of raw material for the forest industry. This study also examined forest management’s impact on carbon storage at a landscape scale, rather than just on a single parcel of land. Since only a portion of NYS’s forests are managed, the study modeled the impact of applying GS to 33% of the forested landscape and found that the carbon stored in the forest was 93% of the base case. This also provided a steady supply of forest products that can be used to make products which also store carbon. To optimize forest carbon storage, provide wood products for the forest industry, and to replace fossil fuels, New York State should encourage forest landowners to manage their forests using GS.

Keywords

Good silviculture, high grading, carbon storage, forest management

Table of Contents

List of Figures

List of Tables

Executive Summary

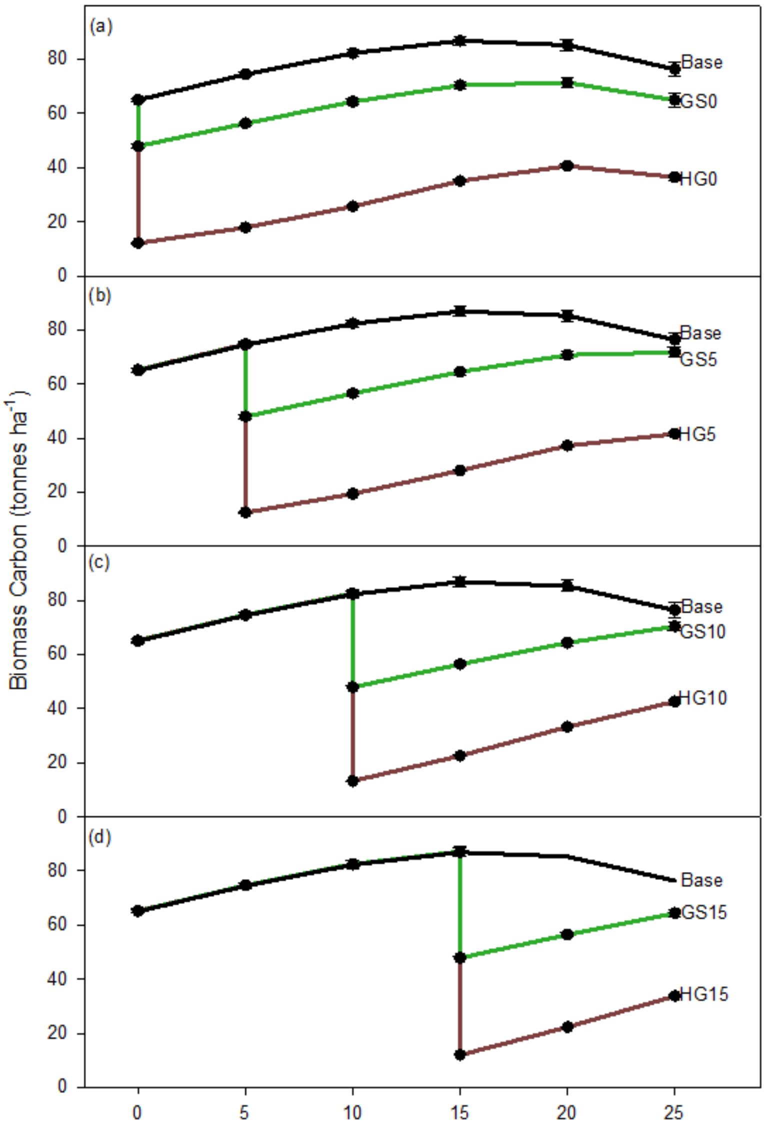
The majority of land (63%) in New York State is covered with forests, 83% of which are classified as timberland, that provide a range of products and ecosystem services (i.e., air and water purification, carbon storage, nutrient cycling, habitat, social and cultural benefits, and traditional uses). There are over 687,000 landowners of forest land in NYS, and the forest industry provides direct employment for almost 41,000 people, generating $23 billion of direct and indirect impacts each year. Forest management and harvesting supply wood products are essential to the continued success of this sector. Understanding how to balance the need for products from forests to support the use of renewable materials and energy, the forest sector, and carbon sequestration and storage is critical to reaching the goals of the Climate Leadership and Community Protection Act (Climate Act).

This study assessed how the aboveground carbon forest pools change in response to management practices including (1) no management, (2) science-based "good silviculture," (GS) and (3) poor management in the form of "high grading" (HG). It used a forest growth simulator developed from measurements of a network of hundreds of forest inventory plots in NYS tracked over several decades. A baseline scenario (no forest management) and 10 other combinations of forest management using either GS or HG were tested and the impact on aboveground forest carbon was assessed.

When GS is used, forest carbon stored in a single stand typically is greater than 90% of carbon stored in the baseline (no management) scenario within 10–20 years of the initial harvest. The projected pattern depends on when the stand is cut because the initial stand conditions at the time of the harvest impact the forest's response (Figure ES-1). In addition to sequestering and storing carbon, GS also generates a more consistent supply of timber and other material that (1) store carbon for short (i.e., a few years for paper and packaging) and long (i.e., decades for some wood used in furniture and housing) time periods and (2) provides raw material that is essential for the forest products and energy industries. When HG is used by landowners, the carbon stocks in the forest are less than 60% of the level in the baseline scenario over the 25-year period modeled—and the forests do not recover enough in 25 years to support another harvest. Poor forest management has long-term negative impacts on forest carbon storage, does not allow landowners an opportunity for additional harvests and revenue over the time period modeled, and will have negative impacts on other ecosystem services provided by NYS forests.

Figure ES-1. Changes in Carbon Stored in Aboveground Biomass (mean ± SD) in a Single Forest Stand under Different Management Scenarios and Timing of Management Scenarios

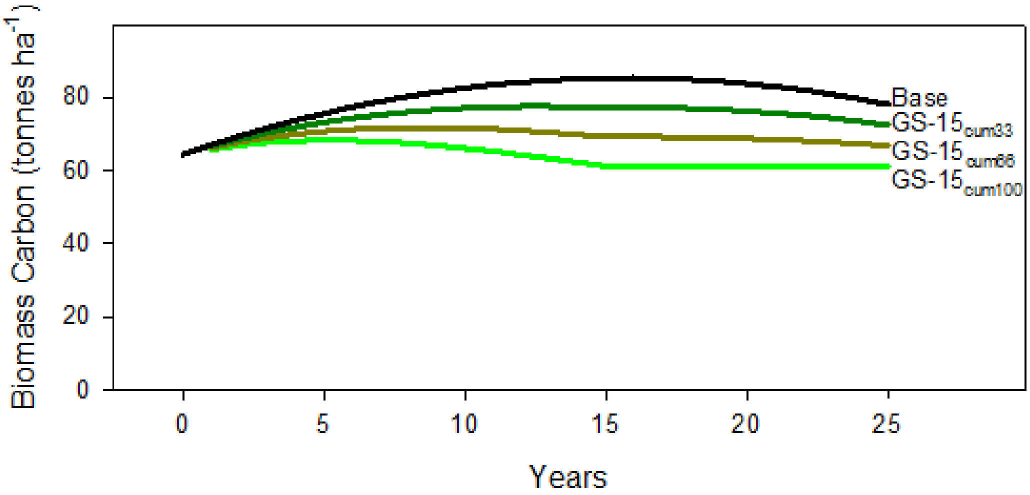
(a) Base is the baseline scenario, which is an unmanaged stand. GS0 is a good silviculture (GS) harvest at year 0 and HG0 is a high-grade (HG) harvest at year 0. GS5, GS10 and GS15 are good silviculture harvests at 5, 10, and 15 years (Figures b, c, d). HG5, HG10, and HG15 are harvests at years 5, 10, and 15 (Figures b, c, d).



Results of this research clearly show that GS needs to be used when managing NYS forests in order to optimize carbon storage and produce products to support forest industry and energy applications. There are additional carbon benefits associated with forest products or energy generated from forest biomass, but they were not assessed in this study. The use of HG dramatically impairs the forest's ability to store carbon and does not allow repeated harvesting within 25 years. While examining the response of a single stand to different forest management practices is informative, it is essential to understand carbon dynamics at a landscape level. Using a landscape perspective shows that when GS practices are applied across 33% or 66% of the forested landscape there is a very small drop in total forest carbon storage while still providing wood products to support forest and energy industries (Figure ES-2). GS is a fundamental part of a strategy to attain forest systems that optimize carbon storage, provide wood products for the forest industry, and to offset fossil fuels. To optimize forest carbon storage, provide wood products for the forest industry, and to replace fossil fuels, New York State should encourage forest landowners to manage their forests using GS practices.

Figure ES-2. Amount of Stored Carbon in Standing Biomass across the Forested Landscape where Good Silviculture is Applied to Different Proportions of the Landscape

GS-15_{100} indicates that GS was applied so that the residual basal area in the stand would allow a second harvest in 15 years and this practice was applied across 100% of the landscape. The GS-15_{66} and GS-15_{33} indicates GS is applied to 66% and 33% of the forested landscape.



1 Background

The majority of land (63%) in New York State is covered with forests that provide a wide range of products and ecosystem services. Of the 7.6 million hectares (ha; 18.7 million acres) of forest cover in the State, 6.3 million ha (15.6 million acres) are classified as timberland, which is defined as forest land that does not have restrictions on timber production and is able to produce more than 1.4 m^3 ha^{-1} yr^{-1}.[1] There are over 687,000 landowners of forest land in NYS and the forest sector generates $13.2 billion of direct output each year as well as an additional $9.8 billion in indirect and induced impact (Cavo et al. 2014). These sectors provide direct employment for almost 41,000 people. Forest management and harvesting to supply a variety of wood products are essential activities to the continued success of this sector. At the same time, these forests provide a wide range of other ecosystem services including air and water purification, nutrient cycling, habitat for a wide range of species, social and cultural benefits such as recreational activities (forest-based tourism is a $1.9 billion sector in NYS), and traditional uses. An ecosystem function of forests that is receiving additional attention is carbon cycling and storage. Understanding how to balance the need for products from forests to support the use of renewable materials, the forest sector, and a wide range of ecosystem services they provide is important.

Carbon stored in forests comes from carbon dioxide (CO_2) that has been removed from the atmosphere, by trees and other plants. Since forests are dynamic ecosystems, the pathways for the carbon that is incorporated into forest systems are complex and change over time. CO_2 removed from the atmosphere can be stored in wood, leaves, roots, and the soil, and some is respired and returned to the atmosphere. The carbon stored in the aboveground components of trees in the forest ecosystem is most often the focus of attention in discussions about forest carbon. This occurs because it is the most visible portion of carbon, the easiest to measure and quantify, and the source of much of the monetary value that is generated from forest systems. The aboveground portion of forests is also the component that is most often the focus of management to meet a variety of objectives, and therefore they are often the crux of questions related to the impact of forest management (Smith et al. 2019).

---

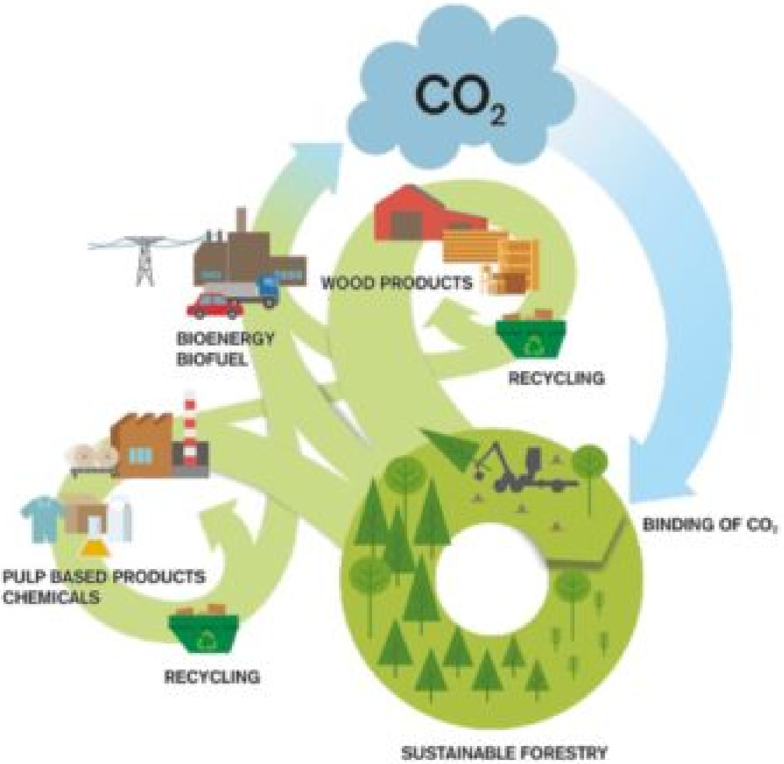
[1] Cubic meters per hectare per year; 20 ft^3 $acre^{-1}$ yr^{-1} [cubic feet per acre per year]; Albright 2018, USDA Forest Service 2016.

When assessing the role that forests can play in carbon management, the entire forest ecosystem, trees, roots, soil and other plants, and the uses of harvested material as solid wood products, paper and packaging material, bioenergy, and/or bioproducts needs to be considered as a whole. The carbon stored in roots and soil is the largest pool in almost any forest ecosystem, and generally increases with latitude. In temperate environments, such as the eastern region of the United States and NYS, these pools will account for over 50% of the carbon in the system (USDA Forest Service 2015). However, information on changes in this and other pools, like belowground biomass, is limited and it is often difficult to predict how these components will change over time, in response to climate change perturbations as well as management activities.

When trees are harvested it reduces a proportion of carbon residing in the aboveground biomass pool and the forest then regrows over time (Figure 1). Although outside the scope of this project, the fate of the harvested material should be considered in overall carbon accounting. For example, timber that is transformed into durable wood products can continue to store the carbon that was in the tree for years or decades depending on the products made and their lifespan. The fate and lifespan of different forest materials should be included in an assessment of forest carbon. Likewise, components of harvested trees that are not used for solid wood products can be used to generate energy such as heat or biofuels and be turned into newer, higher valued bioproducts. This bioenergy and bioproducts can replace fossil fuels (which are derived from geologic carbon, rather than the biogenic-based carbon sequestered in trees) that are currently being used. The benefits associated with this substitution must also be considered when assessing the role that forests can play in addressing climate change.

As noted, the focus of forest carbon accounting is often on the aboveground standing carbon in trees in the system. The purpose of this study was to assess how the aboveground forest carbon pool changes in response to management practices including (1) no management, (2) science-based “good silviculture,” and (3) poor management in the form of “high grading” (HG). The greenhouse gas (GHG) impact associated with harvesting and initial processing practices that occur in forests in the region was also quantified.

Figure 1. The Flow of Carbon though Forest Systems and Various Wood-Based Products and Energy that Result from Management Has Many Different Components (IEA Bioenergy 2018)

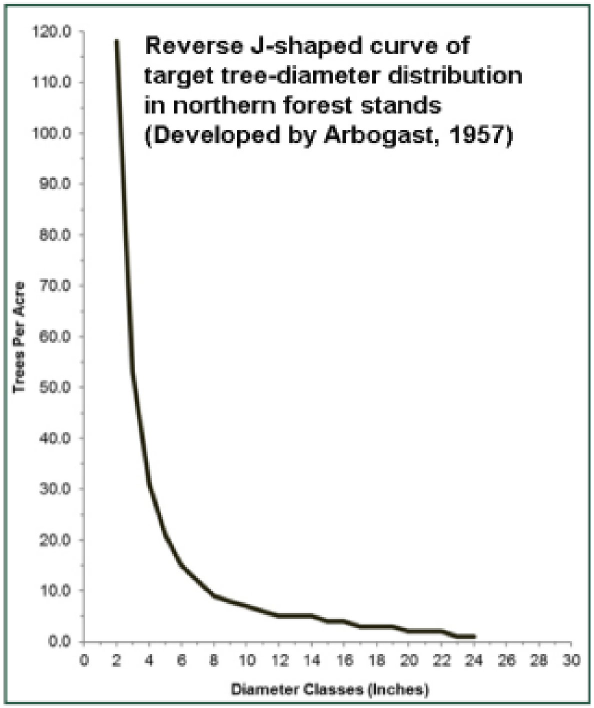


Silviculture is the art and science of applying ecological principles to promote the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society, such as wildlife habitat, timber, water resources, restoration, and recreation on a sustainable basis (USDA Forest Service). The needs of stakeholders are met by understanding their goals and then applying different treatments such as thinning, harvesting, site preparation, planting, pruning, nutrient management, etc. Harvesting or regeneration treatments that are applied to generate wood products, revenue, and age-distributions of new trees in a forest are often grouped into one of the following categories: uneven-aged, two-aged, even-aged, and coppice. Mixed hardwood forests in the northeast U.S. are typically uneven-aged stands, so good harvesting treatments make use of the principles that have been developed for these kinds of stands. An uneven-aged stand contains trees with a wide range of size and maturity, with multiple age classes existing within the same stand. It is structurally and visually unique and has the possibility of offering a variety of market and non-market values that can satisfy a variety of landowner and public objectives. Good management in an uneven-aged silvicultural system must include regeneration, tending, and harvesting occurring concurrently. Each time a stand is accessed for harvesting, some trees in the oldest class are removed to regenerate a new age class and immature age classes are thinned to remove trees that do not have the potential to produce products or services in the future that will meet the landowners' objectives. For example, if one of a landowner's goals is saw timber production, then species such as beech, which are not marketable as sawtimber, are selected for removal over species such as sugar maple or cherry that are valued for saw logs. The task of the silviculturalist or forester is to reduce competition for individual trees that have the growth potential and quality attributes to produce saw logs and improve the long-term health and composition of the forest. Any harvesting and tending operations that occur are done to maintain a balance among the different age classes in the forest to ensure future growth and the capacity of the forest to provide a wide range of ecosystem services such as clean water, fuel, timber, climate mitigation, nutrient cycling, recreation, and cultural heritage values (Balloffet et al. 2012).

Ideally in uneven stands, there should be at least three separate age classes, with each age class occupying approximately equal amounts of space. The number of age classes present in the forest is determined by the maturity age of a class divided by the cutting cycle length. Cutting cycle lengths can vary, and are generally determined by landowners' objectives, tree growth rates, and financial constraints. The cutting cycle length is closely linked to the residual basal area (a measurement that indicates the amount of room trees have to grow, or stocking) after a cutting. If a shorter cutting cycle is required, residual basal area should be higher than if a longer cutting cycle length is desired. With a longer cutting cycle, a greater volume of wood is removed in each harvest but the length of time between harvests is greater to allow for regrowth. A shorter cutting cycle removes less material at each harvest, but the time between harvests is shorter.

A goal of good silvicultural practices is to maintain balanced structure and species composition, which are key to successful and sustainable management of mixed northern hardwood stands, and ensures a consistent, predictable structure that allows for sustained and regular yields from the stand. Past research has recommended that the diameter distribution after cutting resemble a reverse J-shape for a balanced stand for uneven-aged northern hardwoods (Figure 2). This structure has been shown to be stable and provides a sustainable supply of wood products over multiple harvest cycles while maintaining the health and vigor of the forest, so it can continue to provide a range of other ecosystem services. The number of trees allocated to the age classes can be altered to accommodate a variety of financial, timber, ecosystem services, or other landowner objectives (Kenefic and Nyland 2005).

Figure 2. Good Silviculture Should Result in a Stable Diameter Distribution of Trees that Have a Reverse J-Shape (Nyland et al. 2015)



Diameter-limit cuts are harvests where all the trees above a particular diameter are cut, leaving behind only smaller trees. In some cases, only the higher quality large trees are removed, leaving behind some low-quality larger trees and smaller diameter trees (Kenefic and Nyland 2005). This approach is also called high grading. Diameter-limit cutting and high grading are examples of poor silvicultural prescriptions because they fail to take into account the balance in the diameter distribution and stand structure that is needed to support future growth and the ecosystem services that can be provided by the residual forest. High grading is focused on generating the most revenue from the forest at a single point in time with no regard for long-term production and health of the forest. While it is widely recognized that diameter-limit cutting and high grading are not good forest management practices because they generally decrease the genetic quality of trees in a stand, these practices are often implemented across the landscape because of the immediate monetary value they generate and the ease of implementation.

Diameter-limit cuts also negatively impact the wood supply available to current and future markets. It is reasonable to assume that a direct relationship exists between supply and demand for hardwood timber and the level of silviculture currently practiced. Good silvicultural practices that result in a consistent supply of high-quality timber support both the ecosystem and the economic system as well. Diameter-limit cuts alter the current and future stand conditions and structure, and as a result, negatively impact the value for wood production in the future, growth rates, and carbon storage potential. Forest diversity is also negatively impacted in both upper and lower canopy conditions, and at ground level (Perschel et al. 2007, Nyland 1992, Kenefic and Nyland 2005).

2 Methods and Materials

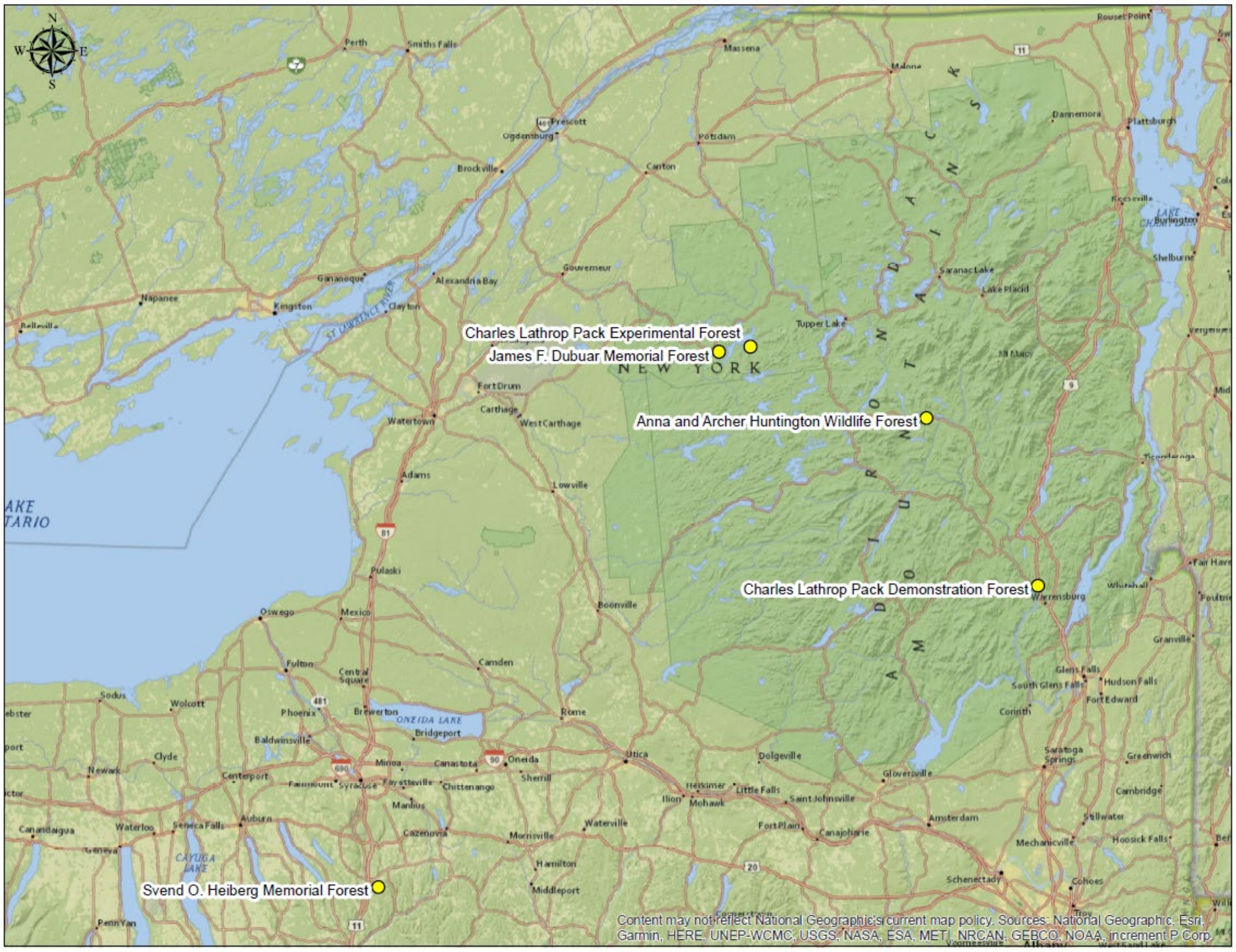
2.1 Available Forest Stand Data

The State University of New York College of Environmental Science and Forestry (SUNY ESF) has been collecting data from a network of 623 permanent plots at five different locations in NYS for up to 50 years. Data was historically collected approximately every 10 years and includes the species and diameter at breast height (DBH) for each tree in the plot (Table 1, Figure 3). The data collected from these permanent plots is the foundation for the forest growth simulator that has been developed and was used for this project. Data from these plots were also used for the initial conditions for model runs where different forest management practices were applied, so that the scenarios started with actual conditions based on field data.

Table 1. Location and Number of Forest Plots and Measurement Years for Long-Term Data Sets Collected by SUNY ESF in NYS

Site	Number of Plots	Years Plots Were Measured
Huntington Wildlife Forest (HWF), Newcomb, NY	171	1970, 1981, 1991, 2001
Dubar Memorial Forest (DMF), Wanakena, NY	72	1989, 1996, 2006
Pack Experimental Forest (PEF), Wanakena, NY	72	1989, 1996, 2006
Heiberg Memorial Forest (HMF), Tully, NY	213	1981, 1990, 2000, 2010
Pack Demonstration Forest (PDF), Warrensburg, NY	95	1983, 1993, 2003

Figure 3. Location of Sites with Permanent Plots that Were Used to Develop the Forest Growth Simulator



Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

A sample of the diameter distributions of the trees in all the forest plots located at the Pack Experimental Forest is provided below (Figures 4 and 5). It illustrates the kind of information that is available from these plots and shows how the stands in the plots have grown and developed over time with a shift toward more trees in the larger diameter classes and fewer trees in the smaller diameter classes. This data on the diameter distribution of the mix of trees in the plots is important information needed to develop good silvicultural prescriptions for the stands (more detail on this below) and to run the forest growth simulator used in the project.

Figure 4. Diameter Distribution for All Trees Greater than 4.5 Inches in Diameter across 72 Measurement Plots at the Pack Experimental Forest (PEF) in 1989, 1996, and 2006

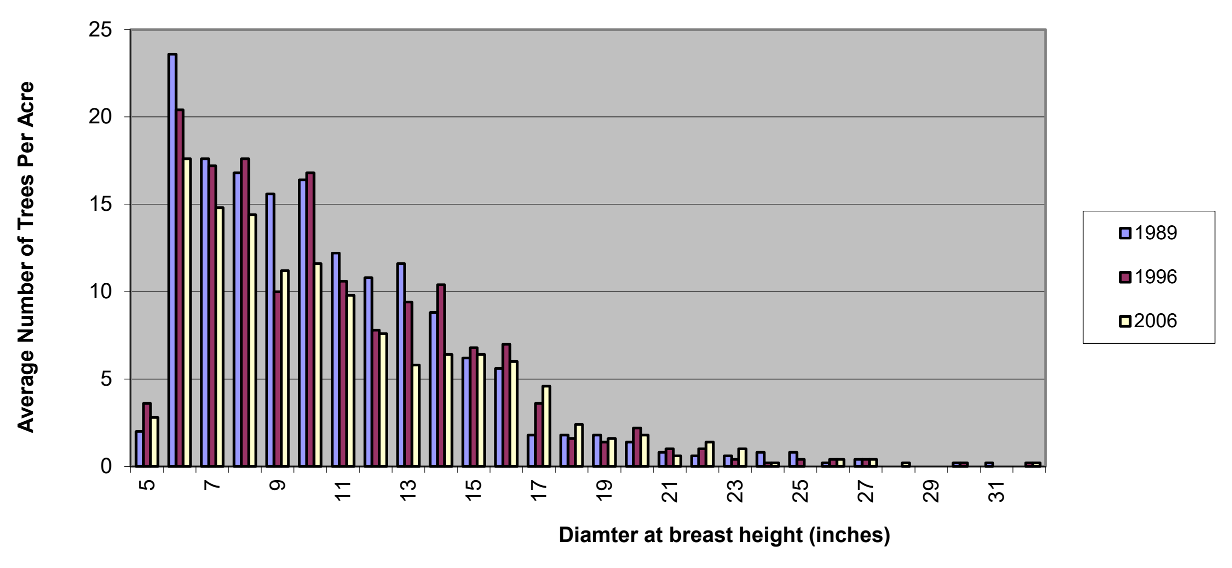
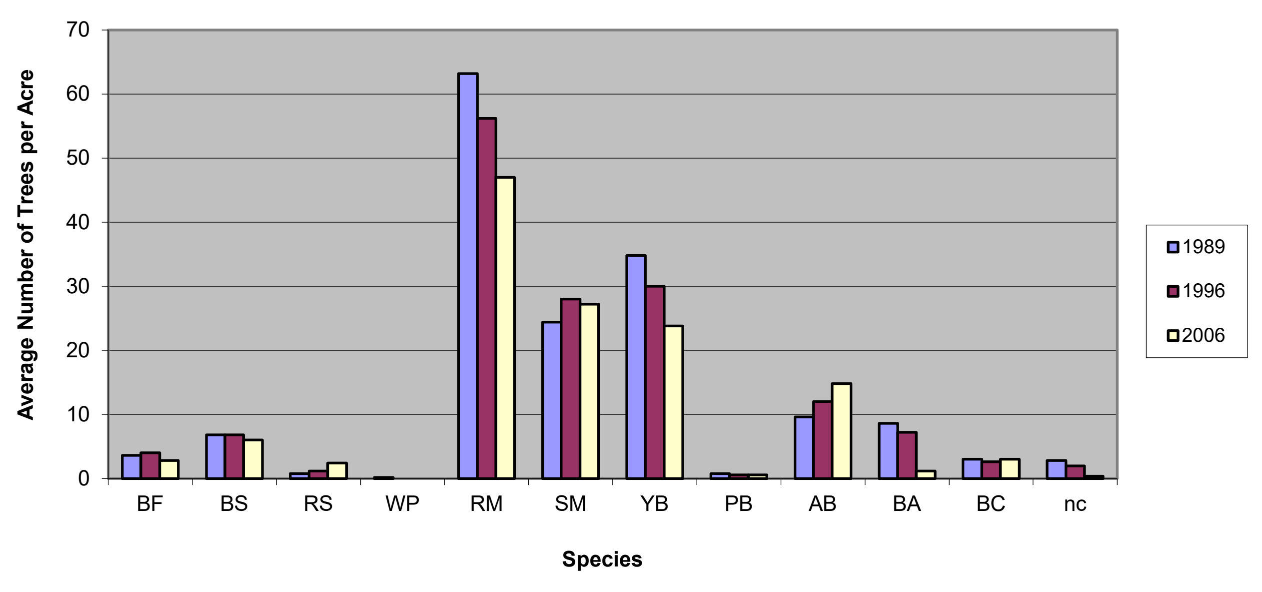


Figure 5. Species Composition of Trees Greater than 4.5 Inches in Diameter across 72 Measurement Plots at the Pack Experimental Forest (PEF) in 1989, 1996, and 2000

(Species codes: BF = balsam fir, BS = black spruce, RS = red spruce, WP = white pine, RM = red maple, SM = sugar maple, YB = yellow birch, PB = paper birch, AB = American beech, BA = black ash, BC = black cherry, nc = not coded.



2.2 Forest Growth Simulator

The forest growth simulator was developed to explore alternative forest stand structures and residual densities (levels of crowdedness) in uneven-aged northern hardwood stands. It is an individual tree model that generates data representing diameter distributions defined by maximum tree size, plot basal area, and a specified stand structure. Tree data are stored in lists representing twenty-five 0.04-ha plots. The simulator repeatedly calls subroutines for growth, mortality, and ingrowth to update the tree list over a series of five-year periods up to 30 years. It allows users to specify initial stand conditions such as tree diameter distributions using stand table data. As a result, users can simulate various types of different harvesting scenarios over consecutive cutting cycles, summarizing the data for each cutting cycle and from multiple simulation runs.

The forest growth simulator used in this project was developed using almost three decades of data collected by SUNY ESF from permanent forest plots. Over this time period, these plots were treated with different silvicultural practices and the responses to these practices were measured and documented. The original version of the forest growth simulator was created in the early 1980s (Hansen 1983), revised in the late 1980s (Davis 1988), and most recently revised in the mid-2000s with new diameter growth and mortality routines (Kiernan et al. 2008, Kiernan et al. 2009). Both the revised diameter growth and mortality modules incorporate stochastic components to reflect the dynamics more accurately in forest stands.

The most recent version of the forest growth simulator includes eleven new modules to represent diameter growth, mortality, ingrowth, and harvest yields based on data collected in NYS from a variety of uneven-aged stands treated with different silvicultural prescriptions (Kiernan et al. 2008). The new diameter growth module is a linear, mixed model that predicts future diameter based on initial tree size, lapsed time, and residual basal area. The new mortality module predicts the probability that an individual tree will die over different time periods based on initial plot basal area, initial tree diameter, and length of time. The general estimating equations (GEE) account for the temporal autocorrelation inherent in data from remeasurement of permanent sample plots in uneven-aged northern hardwood stands under various silviculture systems. Two new stochastic components were included in the diameter growth module. The first randomly assigns an initial size to trees within a 5-cm diameter class (to the nearest 0.1 cm) based on the specified diameter distribution. It does this at the start of each cutting cycle. The second adds a random component to the predicted growth for each tree based on a normally distributed repeated measure error term as specified by the equations from statistical analysis. A stochastic component was also included in the mortality module, whereby the probability of mortality is predicted, and then compared to a uniformly distributed random number. If the random number is less than the predicted mortality, the tree dies. The simulator has biomass equations for the whole tree and tree components, along with carbon conversion fractions to quantify sequestered carbon.

Following the work of Pastor et al. (1984), available whole-tree, above-ground, dry-weight biomass equations from northeastern North America were used in the forest growth simulator to estimate the biomass of different species. The aggregated data were used to develop species-specific biomass models that predicted biomass in each diameter class. The estimated relative error and the mean percent difference were used to compare the generalized predicted values to the predicted values from the original models based on the average deviation between them (Pastor et al. 1984). Correction factors were computed to account for transformation bias that occurs when logarithmic functions are used to estimate biomass from diameter (Baskerville 1972). Carbon content was determined from the biomass estimates for the different species and diameter classes following the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2006, Lamlom and Savidge 2003). Total aboveground carbon for each tree was then partitioned into branches, stem wood, stem bark, and foliage (after Jenkins et al. 2003). Outputs from the simulations are summarized by 5-cm diameter classes for number of trees, basal area, total merchantable volume, total carbon, and carbon content of branch wood, foliage, stem wood, and stembark. Diameter classes are later aggregated into four broad size classes: saplings (1.0-14.9 centimeters [cm]); poles (15.0-29.9 cm); small sawtimber (30.0-44.9 cm); and large sawtimber (≥ 45.0 cm). Output is presented by 5-year intervals over the specified cutting cycle. Twenty-five year re-measurement data was used to create the diameter growth and mortality models. While it is possible to predict outcomes over much longer periods, it is not prudent to predict much beyond the limits of the data used to create these models. Therefore, the analyses conducted as part of this project examined results at the end of the acceptable period of time with a maximum length of a twenty-five-year cutting cycle.

2.3 Scenarios with Forest Growth Simulator

Initially a distribution of forest stands with a mixture of hardwoods, predominately beech, maple, and white ash were selected from various locations in NYS to represent the conditions and to serve as a baseline for the forest growth simulator. Three initial model runs were conducted, and the runs included:

1. Growth over 25 years with no harvesting (baseline scenario).
2. Growth for 15 years and then a harvest based on guidelines for good silviculture in northeast hardwood stands (GS—good silviculture scenario).
3. Growth for 15 years and then a diameter-limit cut (all the trees in a stand over a given diameter are harvested) (HG—high grading scenario).

The GS harvest used well established principles for northeast hardwood stands. The plan was to implement cuts starting with a harvest in year 0 and then allow the stand to regrow. The residual basal area selected was 75 – 80 ft^2/acre (~17.2 – 18.4 m^2/ha) so that the next harvest in the stand could occur in about 15 years. Cutting to a lower basal area is possible but it would extend the time for when it would be reasonable to reenter the stand for a second harvest. Choosing the higher basal area provided an opportunity to have one or more scenarios where more than one harvest could be implemented. The HG cut was a diameter-limit cut where all the trees over a set diameter, 30cm in this case, were removed at the time of harvest.

A limitation of the initial set of runs using the stand characteristics averaged from a number of plots from different locations in that there were not enough trees of the right size in the stand, indicated by the initial basal area, to implement a harvest using good silviculture in year 0. As noted above, the limit set for the residual stand was 75 – 80 ft^2/acre, so there needed to be enough additional basal area above this threshold to generate enough wood products to support a GS operation. The initial stand did not have enough basal area to make a harvest realistic because there was too little material to remove from the forest stand. The initial solution was to take the baseline stand and allow the model to grow the forest for 15 years before implementing the GS and HG harvests (see initial model runs 2 and 3 listed above). The stands were then allowed to grow for an additional 25 years after the harvest. As a result, the stand was grown with the model for a total of 40 years to capture the harvests over the entire time period. However, the results from these model runs showed that the standing biomass and carbon in the stands were decreasing more rapidly than would be expected, especially in the later years of the model run.

One of the issues that became clear is that this approach was using the model to predict forest growth and response to management operations over a 40-year time period. The time frame is longer than much of the data that had been used to develop and calibrate the model, which was likely impacting the results by increasing mortality in the later years of the model run. To address this concern, stands were identified in the forest plot data that had enough basal area (>100 ft^2 $acre^{-1}$) to support a harvest starting in year 0. In addition, the total length of time, including pre- and post-harvest growth, was limited to 25 years which was the maximum length of time measured in the data used to create the models.

The three model runs noted above were conducted again using data from stands with greater than 100 ft^2 $acre^{-1}$ basal area, and then the data was analyzed and summarized. The initial concerns associated with running the model for longer periods of time (up to 40 years) were addressed so then the following set of 11 different scenarios (Table 2) were developed and implemented. The scenarios consisted of a baseline scenario with no harvesting of the stand during a 25-year period of time. A set of paired scenarios where GS and HG harvests are conducted at the same point in time (0, 5, 10 and 15 years into the stands growth) were also evaluated. Finally, there are two scenarios that examine GS scenarios where an initial harvest occurs, either at year 0 or year 5, and then a second harvest is conducted 15 years later, at years 15 and 20, respectively. As noted above, the GS harvest practice was designed so that the residual stand retained enough volume to produce a sustainable cut at the end of another 15-year cutting cycle.

Both the GS and HG harvests were implemented based on the diameter distribution of the stand at the time of harvest. The GS harvest (Figure 6) was designed to adjust the diameter distribution, so it had a reverse J-shape, which has been shown to support growth and development of the residual stand (Nyland 1992) and leave a residual basal area of 75 – 80 ft^2/acre. The top potion of Figure 6 illustrates the baseline diameter distribution of the original stand and of the residual stand after the harvest is completed. The material removed includes some trees of appropriate size and species that would be used as sawtimber. In this project, a cutoff diameter at breast height of 25 cm (10 inches) was used and the carbon stored in the stem wood was reported separately because it is generally used for solid wood products (i.e., flooring, furniture, etc.) that store this carbon for long periods of time. The remaining harvested biomass which includes the bark from the stems, stem wood greater than 25cm (10 inches) DBH, and branches would be available for other uses such as bioenergy production, mulch, or potentially higher value products like biofuels and bioproducts.

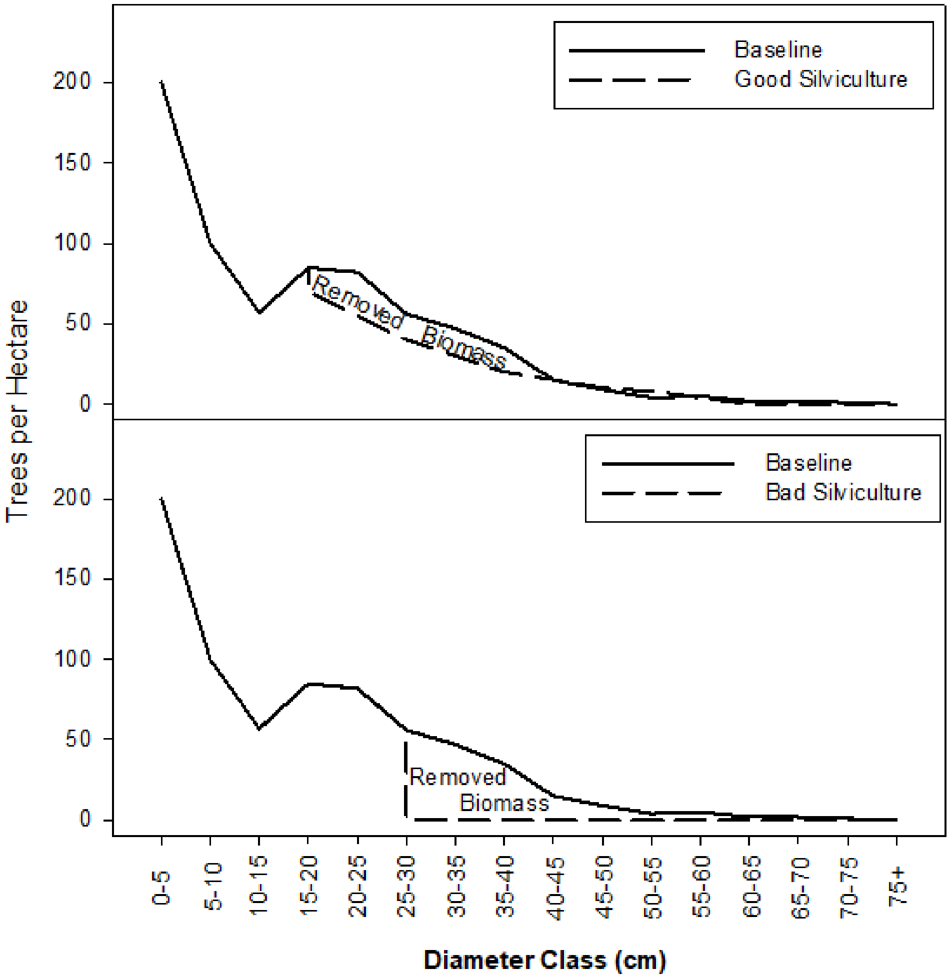
Table 2. Description of the Baseline Scenario and 10 Different Harvesting Scenarios Examined in This Project

Six Good Silviculture [GS] and Four High Grade [HG] Scenarios

Scenario	Scenario Label	Scenario Description
Baseline Scenario	Base	Baseline scenario where the growth model was run for 25 years with no harvesting.
Good Silviculture Harvest at Year 0	GS0	A harvest is applied at year 0 using Good Silviculture and then the growth model was run for 25 years on the residual stand.
High Grade Harvest at Year 0	HG0	A harvest was conducted at year 0 using High Grading principles and then the growth model was run for 25 years on the residual stand.
Good Silviculture Harvest at Year Five	GS5	The stand is grown for five years and then a Good Silviculture harvest was applied at year five. The stand is then grown for an additional 20 years following the harvest.
High Grade Harvest at Year Five	HG5	The stand is grown for five years and then a High-Grade harvest was conducted at year five. The stand is then grown for an additional 20 years following the harvest.
Good Silviculture Harvest at Year 10	GS10	The stand is grown for 10 years and then a Good Silviculture harvest was applied at year 10. The stand is then grown for an additional 15 years following the harvest.
High Grade Harvest at Year 10	HG10	The stand is grown for 10 years and then a High-Grade harvest was conducted at year 10. The stand is then grown for an additional 15 years following the harvest.
Good Silviculture Harvest at Year 15	GS15	The stand is grown for 15 years and then a Good Silviculture harvest was applied at year 15. The stand is then grown for an additional 10 years following the harvest.
High Grade Harvest at Year 15	HG15	The stand is grown for 15 years and then a High-Grade harvest was conducted at year 15. The stand is then grown for an additional 10 years following the harvest.
Good Silviculture Harvest at Year 0 and Year 15	GS0&15	A harvest is applied at year 0 using Good Silviculture and then the growth model was run for 15 years and a second harvest was conducted at year 15 using Good Silvicultural practices. The stand is then grown for an additional 10 years following the second harvest.
Good Silviculture Harvest at Year Five and 20	GS5&20	The stand is grown for five years and then a Good Silviculture harvest was applied at year five. Then the growth model was run for 15 years and a second harvest was conducted at year 20 using Good Silvicultural practices. The stand is then grown for an additional five years following the second harvest.

Figure 6. Diameter Distributions

For the stand used as the baseline for the model runs and the residual stand that remains following the implementation of good silviculture in year zero (scenario GS0, top figure) and high grading in year zero (scenario HG0, bottom figure).



2.3.1 Representation of Landscape Forest Dynamics

All of these scenarios discussed, along with the associated data, represent a single stand in the forest, although each scenario was run 1,000 times to account for variability associated with parameters in the model. The presentation of the data on a stand-by-stand basis makes it easier to identify the impacts over time associated with the different management practices. However, if a wood processing facility that uses wood for end products—ranging from solid wood to paper to bioenergy—relies on a single stand to operate their facility, they would only have a supply of wood once every 15 years, assuming the use of good silviculture. Clearly, wood processing facilities do not operate like this. Instead, they rely on wood supplied from across the landscape so that they have a continual wood supply over time. Thus, a more accurate way to represent the carbon stored in the standing biomass of forests is to include a sustainable supply of material from multiple stands across the landscape and then assess the carbon across these stands.

Only the GS scenarios were able to support enough regrowth to allow a second harvest of a given stand. The decision to set the residual stand basal area at 75 – 80 ft^2 $acre^{-1}$ resulted in a 15-year time period for the stand to recover, so it could be harvested a second time. Because of this time frame, forest carbon dynamics across the landscape were represented using a 15-year time interval using GS practices. Other approaches with different residual basal areas and reentry times could be assessed in the future.

Since the forest growth simulator only provides data once every five years, regression equations were developed that represent the growth response of the forest after it was harvested using GS practices to estimate one-year increments ($R^2 = 0.98$). It was then assumed that there were 15 stands being managed across the landscape and each year one stand was harvested while the other 14 were left to grow. For example, in year zero a single stand was harvested, and 14 other stands were left to grow using the baseline scenario growth rate. In year 1, a second stand was harvested, and 13 stands continued to grow at the baseline rate and one stand was regrowing following the harvest in year zero using the growth rates from the model. An additional stand was harvested each year and the other 14 stands were growing at various rates. In year 15, the stand that was harvested in year zero had regrown enough (see the GS0&15 scenario) that it could be harvested again. A second harvest was implemented each year for 25 years to represent a continuous flow of harvested material from the forest. The standing carbon in each of the 15 stands was then averaged to provide a representation of the standing carbon stored in the forest across the landscape.

Following the same methods just outlined, a landscape scenario was also run that used 20 stands and used a 20-year re-harvest time frame to represent forest stand carbon dynamics. Scenarios using HG management for 15- and 20-year intervals (Regression $R^2=0.93$) were also run, but a second harvest was not possible because regrowth in this stand was not adequate.

It is important to remember that in a forested landscape in any region, seldom are all stands managed simultaneously. There are many parcels where no active management is occurring or planned because they are not a part of a landowners' objectives. The landscape analysis approach just described assumes that 100% (i.e., 15 out of the 15 stands on the landscape) are being managed and harvested once every 15 years. The scenario described above with 100% management of the forest was called GS-15_{100}. In order to represent different proportions of the forested landscape as they were actively managed, two additional scenarios were run, one where 66% (GS-15_{66}) of the landscape was under active management and another where 33% (GS-15_{33}) was under active management. The GS-15_{66} scenario assumes that 34% of the forest landscape is in the baseline scenario where no active management occurs for the 25-year time frame, and the remaining 66% is being actively managed using the GS0&15 scenario. The GS-15_{33} scenario assumes that 67% of the forest landscape is in the baseline scenario where no active management occurs for the 25-year time frame, and the remaining 33% is being actively managed using the GS0&15 scenario.

3 Results and Discussion

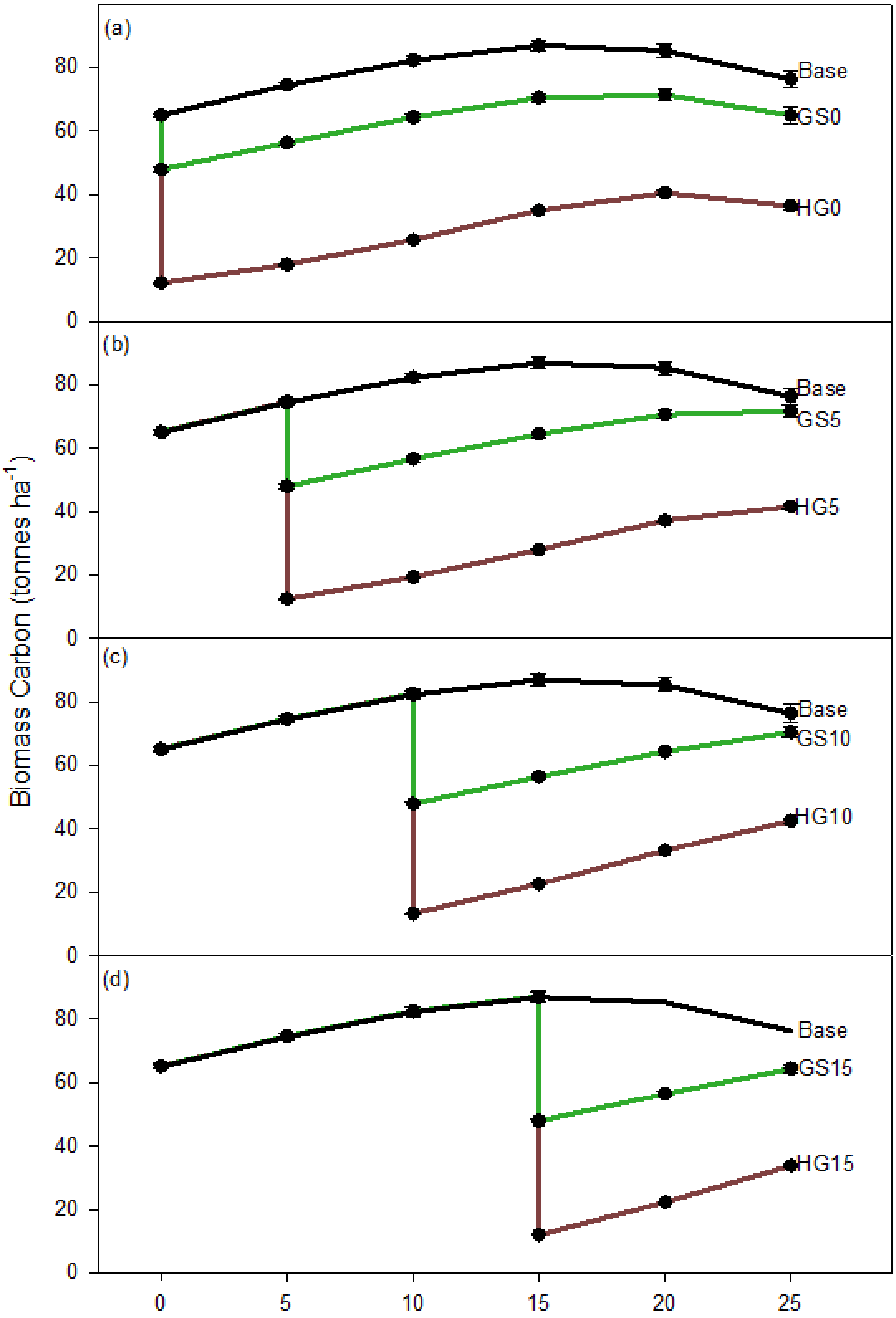
3.1 Single Stand Responses to Different Management Practices

By aligning the timing of harvesting activities among model scenarios and starting with the same stand configuration for each of the 11 scenarios, the effect that specific management actions have on carbon in the standing aboveground biomass relative to the baseline can be examined. The initial stand had 65.0 tonnes of carbon per hectare (Mg C ha^{-1}) at the start of all scenarios. This includes the carbon stored in the stem wood, stem bark, and branches. Carbon stored in the foliage is not included in any of the values reported below because of its rapid turnover. In addition, the model does not account for changes in soil carbon or belowground carbon in the root system of the trees, both of which are important components that should be included in a more complete assessment of forest carbon dynamics. Soil carbon and carbon stored in live belowground root systems can be up to 50% of the total carbon in 100-year-old northern hardwood stands. The live aboveground can make up 30–40% of the carbon in these types of forests with dead wood and forest litter remaining (Catanzaro and D'Amato 2019).

A fully stocked forest that grows and matures over the long term accumulates carbon in the trees, but this does not occur in perpetuity. This is reflected in the baseline scenario where the original stand was allowed to grow using the forest growth simulator for 25 years. The amount of carbon stored in the aboveground parts of the trees reaches a peak after 15 years of growth at 86.8 tonnes ha^{-1} of carbon. This means that over the 15-year time period, the baseline stand has removed 21.8 tonnes of carbon (77.7 tonnes CO_2) from the atmosphere. The amount of standing carbon remains at approximately this level for another five years and then declines slightly to 76.3 tonnes ha^{-1} at 25 years of age (Table 3, Figure 7). A feature of forests as they develop is that individual mature trees will age and die forming gaps. These gaps are subsequently filled, regenerated, and replaced by new growth if it comes from the existing understory, new seedlings seeds, or from some species (like beech) from root or stump sprouts. The result is that carbon stocks reach an equilibrium that may fluctuate between some upper and lower value in perpetuity that is consistent with the forest type, soils, climate, and management. Where forests are managed using either "good" silvicultural (designed to improve stand quality and maintain value over the long term) or "bad" silvicultural practices (which focus on current value in the stand over a certain diameter), new equilibriums other than the baseline may be reached.

Figure 7. Changes in Carbon Stored in Aboveground Biomass (mean ± SD) in a Single Forest Stand under Different Management Scenarios and Timing of Management Scenarios

(a) Baseline is an unmanaged stand, GS0 is a good silviculture harvest at year 0, and HG0 is a high-grade harvest at year 0. GS5, GS10, and GS15 are good silviculture harvests after 5, 10, and 15 years of growth (Figures b, c, and d). HG5, HG10, and HG 15 are high-grading cuts after 5, 10, and 15 years of growth. See Table 2 for a detailed explanation of scenario labels.



The use of good silvicultural practices is an essential part of practicing sustainable forest management and to maintain ecosystem services related to carbon storage while producing useable products and biomass that can be sold by landowners and help maintain forests as forests. When GS is applied in years 0 or 5, the remaining forest stand regrows rapidly and returns to its year 0 level of standing carbon within 15 years. For example, in the GS0 scenario, about 17 tonnes ha^{-1} of carbon are removed (Table 4) in the harvest which lowered the carbon stored in aboveground biomass from 65.0 to 47.9 tonnes ha^{-1}. After 15 years of growth the stand has 70.4 tonnes ha^{-1} of C, which is more than was in the stand at year 0. This indicates that this regrowing stand has removed 22.5 tonnes of C (82.5 tonnes CO_2 ha^{-1}) or that during this time this stand sequestered 16.4 tonnes ha^{-1} C (60.1 tonnes CO_2) from the atmosphere as it regrew. Over the same time period, the baseline scenario removed slightly less (21.8 tonnes ha^{-1} of C or 79.9 tonnes ha^{-1} CO_2) than the harvested stand (22.5 tonnes of C (82.5 tonnes CO_2 ha^{-1}). In addition, and importantly, there were 17.1 tonnes of C that were generated from the GS0 stand that would likely be used for solid wood products or biomass which can contribute to the overall carbon impact of the forest ecosystem.

Table 3. Amounts of Carbon in Standing Aboveground Biomass (tonnes ha^{-1}) for the Baseline Scenario where Growth Occurred for 25 Years with No Harvesting

All the scenarios where a single harvest occurred over the 25-year period used either good silviculture (GS) or high grading (HG). GS0 indicates that a harvest using good silviculture was applied in year 0. GS5, GS10 and GS15 are good silviculture harvests at 5, 10 or years into the stand's growth. HG are high grading cuts at different years in the stand's growth.

Year	Base		GS0		HG0		GS5		HG5		GS10		HG10		GS15		HG15	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	65.0	0.7	47.9	0.7	12.1	0.2	65.1	0.7	65.2	0.7	65.1	0.7	65.1	0.7	65.1	0.7	65.2	0.7
5	74.4	0.9	56.3	1.0	17.8	0.3	47.9	0.7	12.5	0.2	74.6	0.9	74.6	1.0	74.6	0.9	74.6	1.0
10	82.2	1.2	64.3	1.2	25.6	0.5	56.4	0.9	19.4	0.3	47.9	0.6	13.3	0.2	82.5	1.2	82.3	1.4
15	86.8	1.7	70.4	1.5	35.0	0.6	64.5	1.0	28.0	0.4	56.3	0.8	22.6	0.3	47.8	0.6	12.0	0.2
20	85.2	2.1	71.3	2.0	40.7	0.8	70.7	1.3	37.2	0.6	64.3	1.1	33.2	0.5	56.4	0.9	22.3	0.3
25	76.3	2.7	64.9	2.5	36.5	1.1	71.7	1.8	41.6	0.8	70.4	1.5	42.6	0.7	64.4	1.2	33.8	0.4

Table 4. Amounts of Carbon in Standing Aboveground Biomass Harvested in Good Silviculture (GS) and High Grading (HG) Harvests in Northern Hardwood Stands for Eight Different Scenarios

GS0 means that good silviculture were used to harvest the stand at year 0. GS0&15 is the scenario where good silviculture was used to harvest the stand at year 0 and again at year 15. GS5&20 is the scenario where good silviculture was used to harvest the stand at year 5 and again at year 20.

	GS0	HG0	GS5	HG5	GS10	HG10	GS15	HG15	GS0&15	GS5&20
	Tonnes carbon ha^{-1}									
1st Harvest Saw logs	2.4	8.7	3.8	10.1	5.2	11.4	6.5	12.4	2.4	
1st Harvest Biomass	14.7	44.2	22.7	51.7	29.3	57.6	32.4	62.4	14.7	
1st Harvest Total	**17.1**	**52.8**	**26.6**	**61.8**	**34.6**	**69.0**	**38.9**	**74.9**	**17.1**	**26.6**
2nd Harvest Saw logs									3.3	
2nd Harvest Biomass									19.5	
2nd Harvest Total	**0**	**0**	**0**	**0**	**0**	**0**			**22.9**	**22.7**
Total of Harvest 1 & 2	**17.1**	**52.8**	**26.6**	**62.2**	**34.6**	**69.2**			**40.0**	**49.2**

Another approach used to assess the impact of harvesting operations on carbon storage in forests is to compare it to carbon storage in unmanaged stands. A baseline scenario was run so that this perspective could be provided and is clear. At year 0 following the harvest, the GS0 stand has 74% of the stored carbon of the baseline scenario. By 20 years of growth, the amount of carbon stored in the standing biomass of the GS0 scenario is 71.3 tonnes ha^{-1} of C, 83.6% of the amount in the baseline scenario and at 25 years the proportion is about 85%. This provides a perspective between these two scenarios (or the other scenarios presented below) but does not account for the fate of the carbon in the harvested material. Unfortunately, the forest growth simulator model does not capture changes in harvested material that might be left in the stand or the stored carbon in the roots and soils and how these pools change over time.

In the GS0 scenario, 17.1 tonnes ha^{-1} of carbon are removed at the time of harvest; the majority of this carbon (86%) can be used as a feedstock for forest biomass-based energy and/or biofuels. When accounting for carbon associated with forests, it is important to account for the carbon in these different categories because they are part of the overall forest ecosystem. Saw logs used to make solid wood products, which account for the majority of the revenue from harvest, can result in carbon (originally sequestered in the forest) getting locked up and stored in products for many years. Carbon stored in solid wood products and paper products is referred to as harvested wood products (HWP) and the Intergovernmental Panel on Climate Change (IPCC) has developed an approach to account for this stored carbon (IPCC 2013). There still is ongoing debate and discussion on how to account for the carbon stored in HWP products, particularly for wood and the resulting products that move across national borders, but it is increasingly recognized as an important part of the overall carbon accounting of forest systems. The portion of the harvested carbon that ends up in products, the half-life of the carbon storage in different products, and other factors vary and need to be properly accounted for, and then included in the overall accounting of carbon associated with forest ecosystems. Accounting for the fate of the carbon in harvested wood products was beyond the scope of this project.

The majority of the harvested carbon in the GS0 and other GS scenarios is biomass-based products. This is impacted by the diameter distribution of the stand, the proportion of bark and branches in trees, and the GS goal of leaving a well distributed residual stand structure to ensure the future growth and potential for future harvests. The carbon in this material also needs to be accounted for as part of the overall carbon balance of the forest ecosystem. If this material is used to create energy that would otherwise come from a fossil fuel, then the substitution benefit of utilizing this biomass should be accounted for. For example, if the forest biomass was used to produce ethanol using a hot water extraction and fermentation process that was driven using biomass, the GHG emissions would be 20.0 grams of carbon dioxide equivalents per tonne (g CO_{2eq} MJ^{-1};O. Therasme, personal communication, June 21, 2021). In contrast, emissions from E10 gasoline are 89.9 g CO_{2eq} MJ^{-1}. Thus, the use of this forest biomass would reduce emissions associated with transportation by 78% in this case. It is important to recognize this benefit and decide how it will be accounted for as part of the forest ecosystem carbon.

In the GS5 scenario, where a GS harvest is applied after five years of growth, there are 74.4 tonnes of carbon in the aboveground biomass before harvest and 26.6 tonnes of carbon are removed. About 85% of the carbon in this harvest is in the biomass category. Because good silviculture is used and the residual stand is properly distributed across a range of diameter classes, the stand regrows rapidly and after 15 years the stand has 70.7 tonnes of stored carbon, which is 95% of the carbon stored at the time of harvest and 83% of the carbon stored in the baseline stand.

When the stand was allowed to grow for 10 years before it was harvested (GS10), there were 82.2 tonnes ha^{-1} of carbon in the standing biomass at the time of harvest. The good silvicultural harvest removes 34.6 tonnes ha^{-1} and the proportion of the harvested carbon appropriate for biomass-based products is similar to other harvests (85%). Fifteen years later the stand has 70.4 tonnes ha^{-1} of carbon stored in the aboveground biomass. This is 86% of the carbon that was stored in the stand at the time of harvest and 92% of the carbon in the baseline stand. This proportion is slightly higher than other GS scenarios because of the slight decline in standing carbon in the baseline stand at 25 years.

Patterns are similar in the GS15 scenario where the stand is allowed to grow for 15 years before it is harvested. There are 38.9 tonnes ha^{-1} of carbon harvested and 83% of it is in the biomass category. The model is only run for an additional 10 years after this harvest due to the 25-year time limitation imposed for all scenarios. Ten years after harvest, the stand supports 74% of the standing carbon that was present before harvest and 84% of the carbon in the baseline stand. It appears that this stand requires an additional 5 to 10 years for it to return to its original level of stored carbon, but additional years were not included in the model runs because it was beyond the model's 25-year time limitations.

The differences between good silviculture and high grading (or poor silviculture) are apparent across all the scenarios that were run. In all cases where GS and HG were compared at the same time step, the recovery response of the residual forest following harvesting was drastically different (Figure 7). There are no scenarios where HG is applied, and the remaining forest is able to recover and store close to the same amount of carbon that was present at the time of harvest.

For the scenario where HG0 is applied at year 0, 52.8 tonnes ha^{-1} of carbon are removed from the stand. The proportion of the removed carbon that is in the biomass category is 84% and is similar to what was found for the GS harvests. Regrowth over the 25 years following a HG harvest only increases the carbon stored in the aboveground biomass to a maximum of 40.7 tonnes ha^{-1} in year 20. This is only 63% of the standing carbon at the time of harvest (year 0 baseline value is 65.0 tonnes ha^{-1}) and only 48% of the carbon that is stored in the baseline scenario at year 20 (year 20 baseline value is 85.2 tonnes ha^{-1}).

The pattern when the HG is implemented at 5, 10, or 15 years is similar to the HG0 scenario. The stand does not recover to the level of stored carbon that was present at the time of harvest, with the HG5 and HG10 scenarios having 52–56% of the standing carbon compared to what was present at the time of harvest and about 55% of the amount of stored carbon compared to the baseline scenario. The gap is even wider when the HG harvest was implemented at 15 years (39% compared to time of harvest and 44% of the baseline scenario) because the stand only had 10 years to regrow and recover after being harvested.

In all cases, HG generates more total biomass at a single harvest than GS does, but the regrowth in the remaining forest is slow and another harvest was not possible in any of the HG scenarios within the 25-year time frame used with this model. When these harvests are done after 15 years of growth (GS15 and HG15) the HG produces 1.9 times more total biomass than the GS harvest and when the harvest is done in year 0 the HG produced 3.1 times more biomass than GS, but over time the differences are much smaller as will be illustrated below. In all of the scenarios, the majority of the harvested carbon (>80%) was in the biomass category. In addition, the slow recovery of these stands after high grading and the forest's ability to provide other ecosystem services associated with the HG approach to management is negatively impacted (Kenefic and Nyland 2005).

When GS treatments were applied, the forest regrew rapidly enough to allow a second harvest to occur within 15 years, which was the intention of the harvesting design and the residual basal area selected. The GS0&15 and GS5&20 represent the two scenarios where two harvests were possible. The GS0&15 generated 40.0 tonnes ha^{-1} of material in two harvests over a 25-year period and the GS5&20 scenario produced 49.2 tonnes ha^{-1} (Table 5, Figure 8). As with all the harvests, the majority of this material was in the biomass category. For the GS0&15 scenario, the amount of carbon removed in the second harvest is the same as the amount of regrowth that occurred in the stand since the first harvest, indicating that the stand is in essence capturing carbon from the atmosphere at the same rate that it is being removed in harvests. Assuming that GS management continues and that there are no significant disturbances associated (i.e., extreme weather event, pest outbreaks), this pattern of removing CO$_2$ from the atmosphere and then harvesting it and using the material for a combination of solid wood and bioenergy/bioproducts could occur for many years into the future.

The GS0&15 and GS5&20 scenarios with two harvests produced 75–80% of the tonnes ha^{-1} of carbon as the single HG cut. In addition to generating saw logs and biomass, the stand structure for the GS scenarios is maintained, which supports the rapid regrowth rate, supports the resilience of the forest stand, and the provision of other ecosystem services as well. For the GS0&15 and GS5&20 scenarios, it is expected that another GS harvest would be possible in another 15 years after the second harvest, and then total biomass harvested would exceed the HG harvested biomass over a 30-year period. For example, in the GS0&15 scenario the carbon on the standing aboveground biomass at 25 years is essentially the same as the level in year 0 (64.2 tonnes ha^{-1} at year 25 versus 65.0 tonnes ha^{-1} at year 0) and could support another harvest at this point in time. Based on the trajectory and growth rates in the HG scenarios it appears that even after 30 years of regrowth the stand would not return to its original level of carbon stored in standing biomass and would not support another harvest.

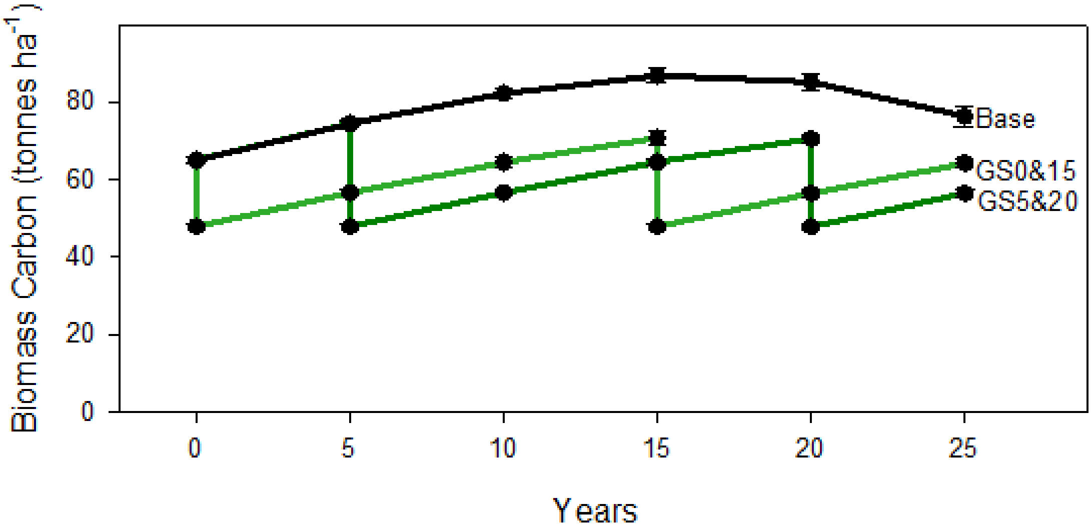
Table 5. Amounts of Carbon in Standing Aboveground Biomass for Scenarios where Good Silviculture (GS) Was Applied and Two Harvests Were Possible over the 25 Years

Years that are repeated indicate the standing carbon before the harvest occurred and what remained after the harvest. GS0&15 indicates that a harvest using good silviculture was applied in year 0 and then again in year 15.

GS0&15				GS5&20		
Year	Mean	SD		Year	Mean	SD
0 (before harvest)	65.0	0.7		0	65.1	0.7
0 (after harvest)	47.9	0.7		5 (before harvest)	74.5	1.1
5	56.6	0.9		5 (after harvest)	47.9	0.7
10	65.5	1.1		10	56.6	0.8
15 (before harvest)	70.8	1.6		15	64.5	0.8
15 (after harvest)	47.9	0.7		20 (before harvest)	70.6	1.2
20	56.4	0.9		20 (after harvest)	47.9	0.7
25	64.2	1.1		25	56.4	0.9

Figure 8. Changes in Carbon Stored in Aboveground Biomass (mean ± SD) in Single Forest Stands under Two Good Silviculture Scenarios where Stands are Harvested Twice During the 25-Year Time Period

Baseline is an unmanaged stand, GS0&15 is a good silviculture harvest at year 0 with a second harvest at year 15. GS5&20 is a good silviculture harvest at year 5 with a second harvest at year 20.

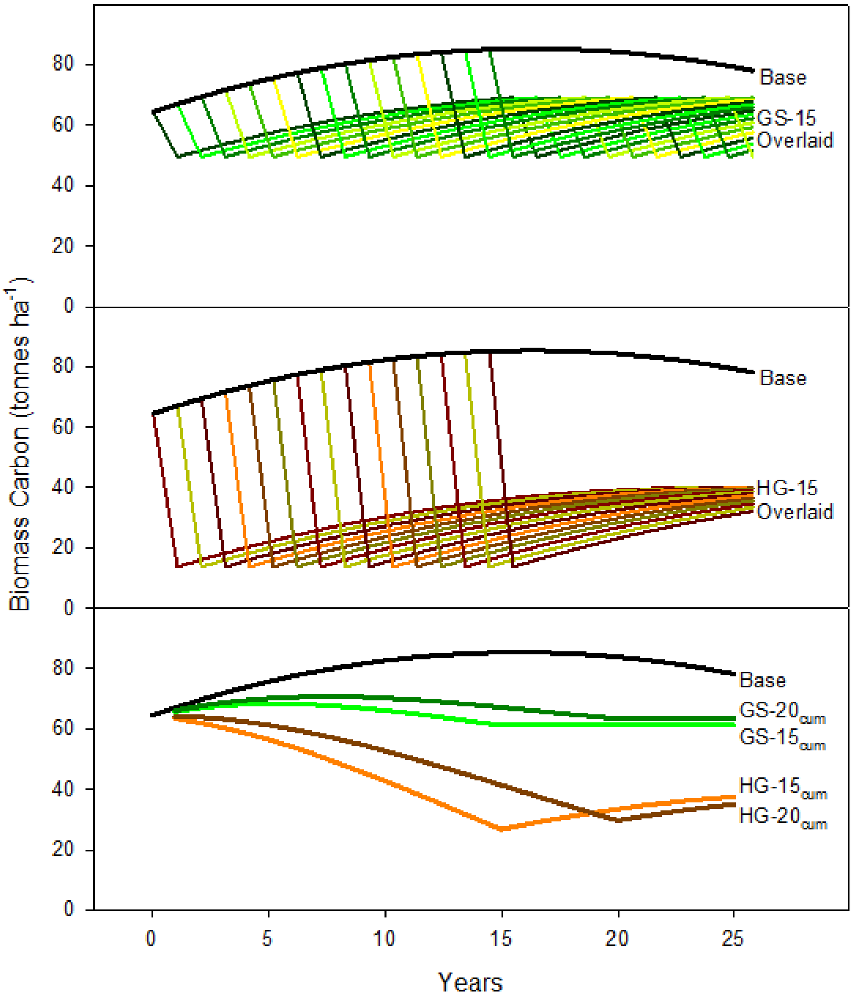


3.2 Landscape Response to Different Management Practices

To understand forest carbon dynamics, it is important to use a landscape approach that incorporates the dynamics of all the stands and their different stages of management. Each of the stands in the GS-15$_{100}$ scenario represents a single stand that was harvested in each of the first 15 years, while the other 14 stands were left to grow (Figure 9a). The stand harvested in year 0 is harvested a second time in year 15. This approach assumes that 100% of the forested landscape is actively managed using GS practices. The carbon stored in the standing biomass across the landscape (the average of all 15 stands) is relatively stable across the 25-year time period, with a very slight increase over the first 10 years from 64.4 to 66.9 tonnes ha^{-1} C followed by a slight decrease to 61.2 tonnes ha^{-1} C at year 15 (Figure 9c). At year nine, the stored carbon in GS-15$_{100}$ is essentially the same (only 3.8% higher) as the stored carbon in year 0 but is 18% less than the baseline scenario. From year 15 to year 25, the standing C stabilizes at 61.2 tonnes ha^{-1} C, and at year 25 the carbon stored in the standing biomass of GS-15$_{100}$ landscape scenario is 78% of the biomass in the baseline scenario. This stable level that occurs starting at year 15 is 5% less than the carbon at year 0 and is 28.3% less than the baseline scenario. In addition to this stored carbon, the GS-15 $_{100}$ had produced 21.4 tonnes of biomass in the form of saw logs and 125.2 tonnes of biomass. The managed stands have maintained an additional 61.2 tonnes of carbon in the standing biomass, all of which was removed from the atmosphere. In contrast, the baseline stand only removed 13.7 tonnes of carbon from the atmosphere over the 25-year time frame. If it was assumed that any mortality in the baseline stand was still stored as carbon, then the amount of carbon removed from the atmosphere would be 21 tonnes of carbon because the peak of stored carbon in the baseline scenario was 85.4 tonnes ha^{-1} at year 16.

Figure 9. Changes in Carbon Stored in Aboveground Biomass across the Landscape under Good Silviculture (GS) and High Grading (HG)

This assumes harvesting occurs every year in order to provide a regular and reliable supply of biomass to end users. (a) Baseline is an unmanaged stand, GS15 represents a single stand that has been harvested every year over the 25-year period (b) HG15 is high grading that occurs every year for the first 15 years. (c) represents the average tonnes ha^{-1} of carbon across all 15 stands (for 15-year cutting cycles), and 20 stands (for 20-year cutting cycle) in each year.



This stable level of carbon in the standing biomass in the GS-15_{100} scenario that occurs after year 15 would be expected to remain across the landscape with ongoing harvesting occurring as long as there were no changes in management or impacts to the forest from pest and disease outbreaks or variations in weather such as drought, early and late frosts, or other potential climate impacts. The stability of the standing carbon across the landscape indicates that a regular supply of forest products would be available, including both saw logs and biomass for bioenergy and/or biofuels over time, without negatively affecting the amount of carbon stored in the standing biomass in the forest across the landscape. Some of this harvested biomass can result in carbon stored in harvestable wood products, and some portion of the biomass fractions could be used to offset fossil fuel consumption for the generation of heat and/or power and biofuels.

The GS-20 scenario that was run follows a similar pattern to the GS-15 scenario, but the GS-20 had slightly higher levels of carbon stored in the standing biomass across the entire 25-year model run. At 25 years, the carbon stored in the standing biomass was 63.4 tonnes ha^{-1} in the GS-20_{100} scenario compared to the 61.2 tonnes ha^{-1} in the GS-15_{100}. This difference is in part due to the fact that the residual basal area selected for all these runs was chosen to allow a second harvest in 15 years. By extending this time period to 20 years, the forest stands store a little more carbon and reach a slightly different equilibrium. A more accurate assessment of a GS-20_{100}, or longer time frames between harvesting events, could be completed by changing the residual basal area of the stand to reflect the longer time frame between harvests.

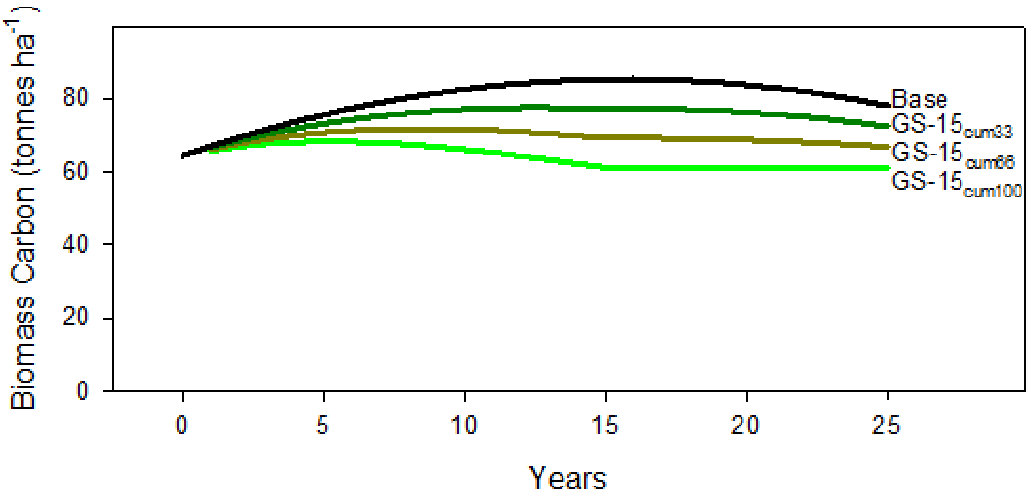
It is not surprising that using the landscape approach with the HG scenario does not change the negative result associated with this approach to harvesting. The HG-15_{100} scenario shows a large decrease in standing carbon for each of the stands when they are cut, and they do not recover enough to be harvested a second time (Figure 9b). As a result, the supply of biomass from these stands stops after 15 years. The landscape stored carbon decreases steadily for 15 years and then increases slightly across all the stands in the HG-15_{100} scenario. By year 25, the stored carbon in the standing biomass across the landscape is only 37.6 tonnes ha^{-1}, which is only 59% of the stored carbon in year 0 and 48% of the carbon in the baseline scenario. The pattern is similar if the HG is spread out over a 20-year time frame.

The landscape scenarios discussed above assume that 100% of the forested landscape is being managed using GS or HG practices. In reality, only a portion of the forested landscape in NYS is being managed at any given point in time. There are a set of complex socioeconomic factors that influence industrial and family forest landowners who have land that is available for management in NYS (i.e., outside of parks, reserves, and other protected areas). The result is a diversity of opinions about what forest management entails and how it is implemented (Munsell and Germain 2007). A previous assessment of forest biomass potential in NYS used a model and estimated that the proportion of forestland that was being managed varied for different counties from 0% to just above 90% (Woodbury et al. 2010). Across the State, the average rate was 49%. The three different levels of forest management intensity modeled bracket this value.

Changing the proportion of the forested landscape that was under management from 100% (GS-15$_{100}$) to 66% (GS-15$_{66}$) and 33% (GS-15$_{33}$) increased the amount of carbon stored in the standing biomass but all three ratios followed similar patterns (Figure 10). By year 25, the GS-15$_{100}$ was at 61.2 tonnes ha^{-1} of stored carbon. Decreasing the portion of the landscape under management to 66% increased that value to 66.8 tonnes ha^{-1}, and at 33% of the area under management the value was 72.5 tonnes ha^{-1}. The baseline scenario stored 78.1 tonnes ha^{-1} so the GS-15$_{66}$ was 86% of the baseline scenario and the GS-15$_{33}$ was 93%. Having a decreasing portion of the forested landscape in GS management brings the level of stored carbon closer to the baseline but does not account for all the carbon stored from these scenarios. Any of these scenarios can also supply a regular, steady supply of biomass that can be used in the forest products industry, storing carbon for different periods of time, and could also be used to supply biomass for heating, power, heat and power, biofuels and/or bioproducts.

Figure 10. Amount of Stored Carbon in Standing Biomass (tonnes ha^{-1}) across the Forested Landscape where Good Silviculture is Applied to Different Proportions of the Landscape

GS-15$_{100}$ indicated that good silviculture was applied so that the residual basal area in the stand would allow a second harvest in 15 years and this practice was applied across 100% of the landscape. The GS-15$_{66}$ and GS-15$_{33}$ indicated that the same good silviculture was applied to 66% and 33% of the forested landscape.



3.2.1 Future Considerations

Biomass that is appropriate for bioenergy and/or biofuels that is harvested from forests in NYS is typically a byproduct of harvesting operations that are occurring because of the production of other products, namely harvesting saw logs. Biomass for bioenergy or biofuels is generally not the main economic driver for harvesting in NYS. Forest harvesting in NYS typically occurs because there are trees in the stand that have a higher value for solid wood products (i.e., flooring, building materials, etc.) or pulp and paper. The portion of the harvested material that is used for energy is typically low value trees or the tops and limbs (residues) of higher value harvested trees that cannot be used for other higher value products.

For all the harvests using good silviculture, the stand was cut so that the remaining basal area would be in the 75–80 ft^2 range using a reverse J diameter distribution as a guide. Cutting to this basal area with the stands used for this project should allow a reentry into the stand for another harvest in about 15 years. Other options that could be explored in the future are for the initial harvest to remove more material, resulting in a lower residual basal area. If done using good silviculture, this would provide more solid wood and biomass material at the initial harvest but extend the time to a second harvest beyond the 15 years (i.e., 20–30 years) used for the scenarios in this project. There are a number of factors that landowners need to consider that influence these decisions and options and they will provide a different response in terms of the carbon stored in the standing biomass.

For harvests that were done using a high-grading scenario, all the trees with diameter greater than 25 cm (10 inches) were harvested and removed from the stand at the time of cutting. There are other options and approaches used when forest stands are high graded that could be explored, but these choices would also not be expected to support vigorous regrowth and restoration of carbon stored in the aboveground biomass or allow for ongoing regular harvests of these stands and sustainable forest management.

When assessing the carbon stocks and flows in forest systems, it is important to not limit the assessment to just the forested area on the ground where harvesting occurs. The regrowth of the forest on the specific parcels that have been harvested are only one of the factors that need to be considered when assessing changes in forest stocks. There are other areas of forest that are being managed in the area and will be supplying products and energy to the same end users over time. While there are decreases in carbon stocks when a forest is harvested, this removal is being balanced by growth that is occurring in other forested areas that have been harvested previously or will be harvested in the future.

This report examines this issue of how carbon in aboveground standing biomass changes across the landscape by taking the results of a single stand analysis and extending it to represent 15 managed stands that make up 33–100% of the landscape. While this provides insight on the importance of forest carbon across the landscape, it is limited by using a single stand with a common starting point and diameter distribution to represent these changes. The forested landscape is not this uniform and future assessments should consider a more dynamic representation of forest landscape dynamics.

While the carbon stored in standing biomass in forests is often the focus of attention in discussions, a much greater proportion of forest carbon is found in the soil, roots, and litter. The dynamics of these components are less well understood but need to be included when planning for the role that forests will play in addressing climate change in NYS.

Wood that is harvested from forests is used for a range of different products ranging from solid wood products like flooring or building timber, to pulp and paper, to bioenergy. As an integrated bioeconomy develops here in NYS and other regions, forests will also supply the raw material for the production of a range of bioproducts and biofuels that are currently made from fossil fuels. It is important to track the flows of harvested material beyond the edge of the forest and through the different pathways because they vary in terms of carbon storage. Harvested material that is characterized as sawtimber is typically made into the solid wood products. When sawtimber is processed, a portion of the stem ends up in solid wood products but a portion of the tree (e.g., tops and branches) and material from the saw log (bark and residues generated when products are manufactured) can be used in other processes. Residues that are generated from this process can be used to make particle board, paper products, pellets, or converted directly to bioenergy either on site or sold to another end user. Solid wood products typically have lifespans of several decades and as a result extend the carbon storage of forests well into the future. Other uses for residues from the sawtimber process have a range of carbon storage potential from a few decades to a few months depending on the product and how it is used. Some materials may be reused or remanufactured so they can be included into other products. For example, the deconstruction of buildings and the recovery of wood materials ranging from flooring and paneling to structural members will further extend the period of time that carbon is stored. Other portions of the harvested material can be used as feedstock to produce renewable energy in hard to decarbonize sectors like heating and transportation or made into bioproducts currently made from fossil fuels. The length of time that these materials store carbon and their substitution benefit when they replace fossil fuels needs to be considered. The fate of this stored carbon and their substitution benefits needs to be included in the overall assessment of the carbon cycle associated with forests.

3.3 Life-Cycle Analysis of Forest Harvesting System

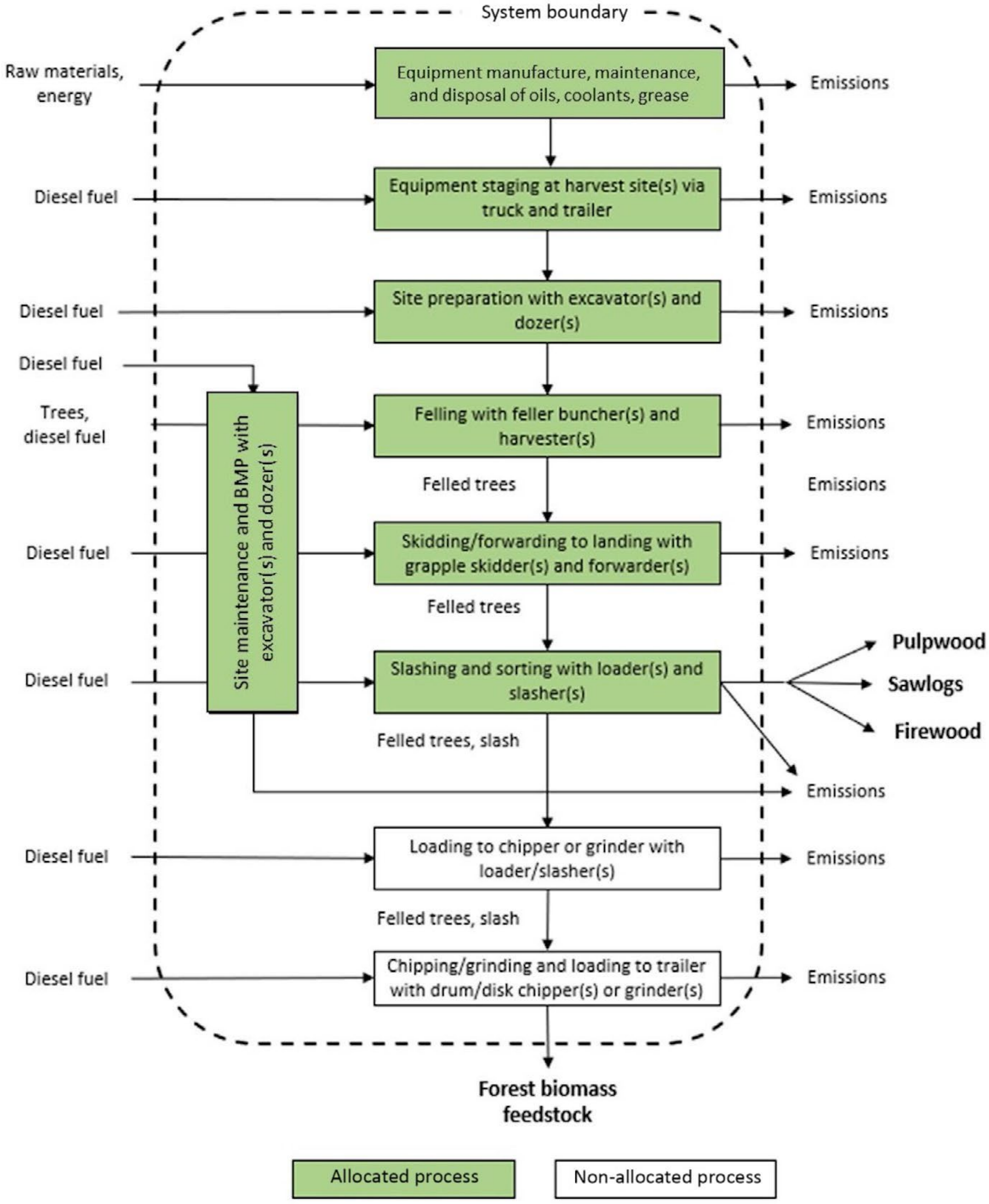
In order to understand the overall GHG impacts associated with forests and the use of harvested material for solid wood products, paper, and/or biomass for energy, it is important to understand all components of this system. This includes the growth in the forest and changes in carbon pools over time, and the GHG impacts associated with management activities, such as those associated with harvesting operations, transportation of materials to end users, and conversion of the harvested wood into final products. The end uses for the biomass fraction of the harvested material in this project is used primarily for heat and power production in NYS (Note that the majority of the funding support for this work was provided through a USDA funded project to SUNY ESF).

There is limited data available on the harvesting and processing steps of the forest biomass fraction of the material that is harvested from forests. Previous studies focused on the harvesting and production stage were focused on saw logs or pulpwood (O'Neil et al. 2010) or did not include the impacts associated with processing the forest biomass material based on operational data from the field (Saud et al. 2013), were limited in their geographic scope (Abbas and Handler 2018), or did not report the data on forest biomass harvesting and processing as part of a larger system such as using pellets for wood heat (Buchholz et al. 2017). There is a need to collect and analyze data for harvesting and processing of forest biomass in the NYS and surrounding regions to fill this gap in knowledge so that a more precise complete system analysis can be conducted for forest biomass and other wood products here in NYS and the surrounding region.

Results from this work, published in Quinn et al. 2020, is the most comprehensive on this topic. It quantified the life-cycle GHG emissions from the production of a forest biomass energy feedstock in the Northeast U.S. as part of harvests generating multiple products, identified the highest-impacting processes of the production system and differences in life-cycle GHG emissions between feedstock types, and compared results with other forest biomass feedstock life-cycle assessments (LCAs) in the literature. This study focused on the operations from logging equipment manufacturing, staging of equipment, harvesting of trees in the forest, skidding and processing of the trees into different products, loading into trucks, and the implementation of best management practices (BMPs) at the harvesting site to minimize impact on water and soil quality (Figure 11).

Data from forest harvesting operations was collected from eight different operations, five of which were in NYS and four in Maine, Massachusetts, and Vermont, and covers almost 10 years of in-woods operations. Multiple products (i.e., chips, ground material, saw log, pulpwood, and firewood) were tracked in these operations with almost 350,000 tonnes of dirty chips and 1.4 million tonnes of clean chips produced. In addition to the product mix that was harvested, there was information on types of equipment, hours of operation, and fuel consumption that will be essential to building robust and reliable models of these systems for the LCA. The range of operations and time period covered provided confidence that the variability of these systems has been captured and can be reflected in future analysis.

Figure 11. System Diagram for Study of GHG Impacts of Forest Biomass Harvesting and Processing (from Quinn et al. 2020)



The shared operations in the forest harvesting operations, such as harvesting and skidding, implementation of BMPs, and staging of equipment, were shared among different products (i.e., saw logs, pulpwood, dirty and clean chips). Thus, both mass and economic allocation approaches were able to be used to distribute the associated GHG emissions among the different products.

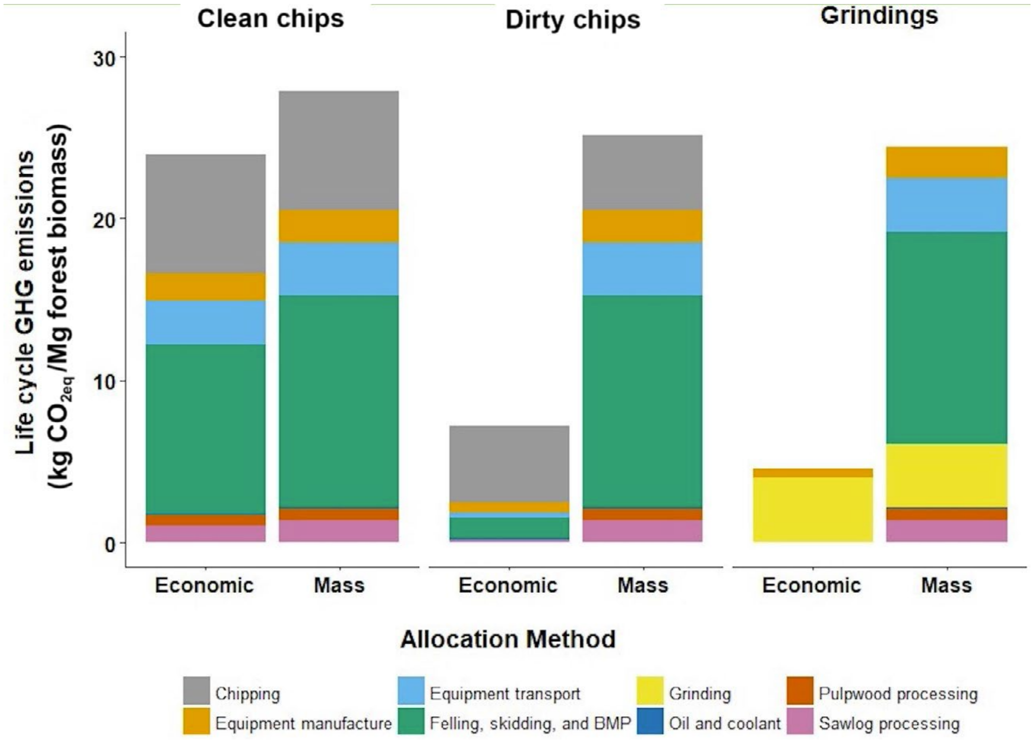
The baseline results of the LCA of these operations showed that the choice of the allocation methods has an impact on the overall GHG emissions (Figure 12). Economic allocation had a lower GHG footprint for the three forest biomass products (clean and dirty chips and grindings). GHG emissions were 4.6 (grindings) to 24.0 (clean chips) kilograms of carbon dioxide equivalents per megagram (kg CO_{2eq} Mg^{-1}) using the mass allocation. The differences were smaller using the mass allocation method ranging from 24.4 kg CO_{2eq} Mg^{-1} for grindings to 27.9 kg CO_{2eq} Mg^{-1} for clean chips. This highlights the impact that the allocation method can have in this kind of analysis. Both of these allocation methods were acceptable and used, but the choice of the method clearly had an impact on the result of the analysis.

The impact of the different steps in the harvesting and processing operations for the different types of biomass demonstrated that felling, skidding, and BMPs followed by either the chipping or grinding step were the main factors contributing to overall GHG emissions. The majority of the impact in these categories were associated with the consumption of diesel fuel, indicating that the use of green diesel in the equipment used for these operations could help to lower the overall GHG footprint.

Figure 12. Baseline Greenhouse Gas Emissions for Three Types of Forest Biomass in the Northeast U.S.

The types were clean chips, dirty chips, and grindings based on two different allocation methods.

The impact of different steps in the harvesting and processing of the types of biomass is illustrated (from Quinn et al. 2020).



4 Conclusions

A large portion of the forest area in NYS is classified as timberland and has the potential to and can be used for the production of wood products. The type of management used on these 6.3 million ha (15.6 million acres) of forests will have a real impact on carbon storage in forests. This study contrasted the impacts of good silvicultural (GS) practices and a poor management practice, high grading (HG), on the carbon stored in standing biomass in forests and also quantified the GHG impact associated with harvesting operations. There were no scenarios where regrowth following HG allowed the forest stand to return to the level of carbon storage that it had prior to the harvest over the 25-year time frame of this project, and it appears that it will take many more years for this to occur. As a result, stands that are high graded can only be harvested once so the supply of material from this kind of management is limited. Poor management practices like high grading have negative impacts both in terms of carbon uptake and storage as well as providing material to support the forest sector and the developing bioeconomy. Steps should be taken to address these poor management practices, so the potential of forests can be realized.

The stands where GS was applied were able to return to the same level of carbon storage that they started with in 15 to 20 years. This rapid regrowth is in part due to the balanced residual forest structure with a range of diameter classes and species that is intentionally left in the forest as part of GS practices. As a result, these well-managed forests took up large amounts of carbon over a relatively short period of time and these rates of growth were greater than uptake in the baseline or unmanaged scenario. In several scenarios where a single GS harvest was implemented, the level of carbon stored in the standing biomass of these stands were very close to what was stored in the baseline scenario at the end of the 25-year time period.

The use of GS practices means that stands can be harvested repeatedly to provide a regular and sustainable supply of wood and biomass to end users. In this case, the GS practice was designed so that the forest would regrow and have enough biomass in the stand for a second harvest in 15 years. The interval for re-harvesting can be changed at the time of the first harvest by adjusting the residual stand using GS principles. A well-designed and implemented forest management system using GS practices is a catch and release type of system where CO_2 is removed from the atmosphere and stored in standing biomass, and then a similar portion of biomass or carbon is removed at the next harvest. This approach to management has the potential to supply wood material to both developed and developing sectors and help address issues related to climate change mitigation.

While examining the dynamics of a single stand, it is important to understand the dynamics of carbon in standing biomass as well as to recognize that the changes across the forest landscape need to be considered. This study extended both GS and HG practices across the landscape by harvesting a single stand each year for 15 years. As with single stand dynamics, HG had negative impacts on both the level of carbon stored in standing biomass in forests and the potential to supply material for products and materials. In contrast, GS practices resulted in a stable level of carbon stored across the landscape and a steady and sustainable supply of wood production. The level of stored carbon was similar to the amount of carbon in standing biomass at the time of the initial harvest. With good silviculture, forests will continue to take up and store carbon at stable levels and wood for a range of materials and products can be generated.

Recognizing that only a portion of the forested landscape (i.e., timberland) that can be managed, will be managed, this study presented three levels of GS management across the landscape (100, 66, and 33%). Previous estimates suggest that less than 50% of the forested landscape in the State is being managed and this varies from region to region. When only 33% of the forested landscape is managed, the stable level of stored carbon across the landscape is only slightly lower than what was found for the baseline (at 25 years, 93%). This gap is slightly larger for the 66% (86%) and 100% (75%) scenarios but it also means that more wood is being harvested and supplied to the forest sector or developing bioeconomy. It is important to understand the carbon dynamics associated with this wood that is harvested in these scenarios and the various products that can be made and how it impacts the overall carbon balance of these systems.

5 References

Abbas, D., and R.M. Handler. 2018. Life-cycle assessment of forest harvesting and transportation operations in Tennessee. *Journal of Cleaner Production*, *176*, 512–520. https://doi.org/10.1016/j.jclepro.2017.11.238

Albright, T.A. 2018. Forests of New York, 2017. Resource Update FS-170. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 4 p. https://doi.org/10.2737/FS-RU-170

Arbogast, C., Jr. 1957. Marking guide for northern hardwoods under the selection system. USDA Forest Service Station Paper 56.

Baskerville, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. Can. J. For. Res. 1:49-53.

Balloffet, N., R. Deal, S. Hines, B. Larry, N. Smith. 2012. Ecosystem Services and Climate Change. (February 4, 2012). U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. www.fs.usda.gov/ccrc/topics/ecosystem-services

Buchholz, T., J.S. Gunn, and D.S. Saah. (2017). Greenhouse gas emissions of local wood pellet heat from northeastern US forests. Energy, 141, 483–491. https://doi.org/10.1016/j.energy.2017.09.062

Catanzaro, P., and A. D’Amato. 2019. Forest Carbon: An essential natural solution for climate change. University of Massachusetts Amherst.

Cavo, M., J. Wagner, D. Newman. New York State Forest Industry: An economic review -2014. https://woodproducts.ny.gov/system/files/documents/2018/07/nys-forest-industry-2014-final-draft.pdf

Davis, R.S. 1988. A simulation of the effects of repeated partial cutting on the structure and development of uneven-aged sugar maple stands in New York. M.S. thesis. SUNY Coll. Environ. Sci. and For. Syracuse, NY.

Hansen, G.D. 1983. Development and application of a computer simulation model to evaluate the effects of different residual diameter distributions on 30-year growth of uneven-aged northern hardwood stands. Ph.D. diss. SUNY Coll. Envir. Sci. For. Syracuse, NY 550p.

International Energy Association Bioenergy. 2018. Is energy from woody biomass positive for the climate? https://www.ieabioenergy.com/wp-content/uploads/2018/01/FAQ_WoodyBiomass-Climate_final-1.pdf

Intergovernmental Panel on Climate Change (IPCC). 2006. Guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston, H.S., Buendia, L. Miwa, K., Ngara, T., and Tanabe, K. (Eds.). Pub: IGES, Japan.

Intergovernmental Panel on Climate Change (IPCC), 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol, T. Hiraishi, et al., Eds. (Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2014). http://www.ipccnggip.iges.or.jp/public/kpsg/pdf/KP_Separate_files/KP_Chapter_2_Methods_Estimation_Measurement_Monitoring_Reporting.pdf. Accessed 10 April 2018

Jenkins, J., D. Chojnacky, L. Heath, R. Birdsey. 2003. National-scale biomass estimators for U.S. tree species. For. Sci. 49:12-35.

Kenefic, L. and R. Nyland. 2005. Diameter-limit cutting and silviculture in Northeastern Forests. USDA Forest Service, Northeastern Area State and Private Forestry, NA-TP-02-05.

Kiernan, D., E. Bevilacqua, and R. Nyland. 2008. Individual-tree diameter growth model for sugar maple trees in uneven-aged northern hardwood stands under selection system. Forest Ecology and Management. 256:1579-1586.

Kiernan, D., E. Bevilacqua, R. Nyland, and L. Zhang. 2009. Modeling tree mortality in low to medium-density uneven-aged hardwoods under selection system using generalized estimating equations. Forest Science. 55:343-351.

Lamlom, S.H. and R.A. Savidge. 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. Biomass and Bioenergy. 25:381-388.

Munsell, J.F. and R.H. Germain. 2007. Woody biomass energy: An opportunity for silviculture on non-industrial private forestlands in New York. Journal of Forestry. 105(8): 398-402.

Nyland, R. D. 1992. Exploitation and Greed in Eastern Hardwood Forests. Journal of Forestry 90(1):33-37.

Nyland, R., E. Bevilacqua, D. Kiernan, A. D'Amato, L. Kenefic and C. Kern. 2015. Selection cuttings sustain uneven-aged Northern Forests but not even-aged. https://nsrcforest.org/sites/default/files/uploads/nyland15.pdf

O'Neil, E. E., L.R. Johnson, B.R.Lippke, J.B. McCarter, M.E. McDill, P.A. Roth, and J.C. Finley. (2010). Life-Cycle impacts of Inland Northwest and Northeast/North central forest resources. Wood and Fiber Science, 42(0), 29–51.

Pastor, J., J.D. Aber, and J.M. Melillo. 1984. Biomass prediction using generalized allometric regressions for some Northeast tree species. For. Ecol. Manag. 7:265-274.

Perschel, R.T., A.M. Evans, and M. Summers. 2007. Climate change, carbon and the forests of the northeast. Forest Guild. https://www.nrcm.org/wp-content/uploads/2013/09/ForestGuild_climate_carbon_forests.pdf

Quinn, R.J. H. Ha, T.A. Volk, T.R. Brown, S. Bick, R.W. Malmsheimer, M-O. P. Fortier. 2020. Life cycle assessment of forest biomass energy feedstock in the northeast United States. Global Change Biology Bioenergy. DOI: 10.1111/gcbb.12725

Saud, P., Wang, J., Lin, W., Sharma, B.D., & Hartley, D.S. 2013. A life cycle analysis of forest carbon balance and carbon emissions of timber harvesting in West Virginia. Wood and Fiber Science, 45 (3), 250-267.

Smith, J. E., G.M. Domke, M.C. Nichols, and B.F. Walters. 2019. Carbon stocks and stock change on federal forest lands of the United States. Ecosphere 10(3):e02637. 10.1002/ecs2.2637

USDA Forest Service. 2015. Baseline Estimates of Carbon Stocks in Forests and Harvested Wood Products for National Forest System Units; Eastern Region. 43 pp. Whitepaper. http://www.fs.fed.us/climatechange/documents/EasternRegionCarbonAssessment.pdf

USDA Forest Service. 2016. Forest inventory and analysis glossary. https://www.nrs.fs.fed.us/fia/data-tools/state-reports/glossary/

USDA Forest Service. Silviculture. https://www.fs.fed.us/forestmanagement/vegetation-management/silviculture/index.shtml. Last Accessed 08/25/2020.

Woodbury, P., T. Volk, R.H. Germain, P. Castellano, T. Buchholz, J. Wightman, J. Melkonain, H. Mayton, Z. Ammed, and C. Peters. 2010. Appendix E: Analysis of sustainable feedstock production potential in New York State. In Renewable fuels roadmap and sustainable biomass feedstock supply for New York. NYSERDA, Albany, NY. 110pp.

New York State
Energy Research and
Development Authority

17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov

State of New York
Kathy Hochul, Governor

New York State Energy Research and Development Authority
Richard L. Kauffman, Chair | Doreen M. Harris, President and CEO