

**Forest Age Class Change Simulator (FACCS):
A spreadsheet-based model for estimation of forest
change and biomass availability**

by

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**Technical Report
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Abstract

The Forest Age Class Change Simulator (FACCS) was developed as a spreadsheet-based model and computational tool to estimate current and future timber and biomass available under user-defined management scenarios and harvest intensities. The model relies on existing data sources and forest management information to produce forest type specific biomass estimates over multiple spatial and temporal scales. This report describes the development of the basic model and its evolution to the present Version 1.3 (dated 8/20/2013) with examples of recent model applications and potential uses. Finally, the model code in Microsoft Excel together with example parameters, run specifications and sample data is described and made available to potential users.

Introduction

Recent state energy legislation and federal action has led to renewed interest in the use of forest biomass for energy production (Becker et al. 2011). In turn, expansion of forest-based bioenergy markets has created interest in the current and future physical, social, economic, and environmental availability of roundwood and residual biomass in the state. While current physical availability can be estimated using data from the Forest Inventory and Analysis (FIA) program within the USDA Forest Service, the attribution of harvesting limitations, annual harvest levels, management practices, and/or market pressures is not readily available in the estimates. A variety of computer models and decision support systems have been developed to accommodate a complex array of decisions and constraints associated with the production, procurement, and utilization of forest biomass (Mitchell 2000, Freppaz et al. 2004, Frombo et al. 2009). While these tools have been useful for informing bioenergy project proposals and supply assessments, they are often limiting due to data needs, required modeling expertise, and limited software flexibility.

The first version of Forest Age Class Change Simulator (FACCS) was developed to project and evaluate the physical availability of forest biomass under a variety of forest management and utilization scenarios, but without the limitations noted above. It was developed as the main component of a support system to aid an energy developer interested in biomass availability and the carbon emissions associated with the use of harvest residues for energy (Domke et al. 2008, 2012). It was designed using a spreadsheet platform familiar to a wide range of potential users and applications. The platform also allowed for a broad range of estimates, e.g., biomass supply and carbon emissions and sequestration. In the process of developing these estimates the model also considered merchantable timber volumes and corresponding biomass.

Model Development

The general form of FACCS was based on the literature of forest projection models (see Alig et al. 1984, Cubbage et al. 1993). It was designed to cycle forest area through a matrix comprised of individual age classes and the project planning horizon. In its simplest form, the model functions by implementing changes in the acreage by one-year age classes and forest type. In an early application of the model, for example, the acreage in each one-year age class was estimated for each forest type from a user-defined FIA inventory period. Then, the acres in each age class were assumed to move (grow) to the next year age class annually. As the acres cycled through age classes, a volume and biomass estimate appropriate to that age class was assigned to the new acreage. To grow the forest over a 30-year planning horizon, for example, the above steps were repeated thirty times. Area in the older age classes, if not harvested, was assumed to die (eventually) and return to the year one age class in each forest type in order to create a closed system for the forest type with no loss of area over the 30-year planning horizon.

The estimates produced by the model are directly related to the length of the user-defined planning horizon and model inputs (i.e., mortality rates, harvest assumptions, biomass yield models, forest area estimates by age class). For this reason it is important that current data

specific to the project area be used when possible and that the assumptions related to disturbance (i.e., mortality rates) and management (i.e., harvest rates) be reflective of the conditions the users are attempting to model. In cases where particularly long planning horizons are desired, the model could be modified to indicate forest type change and succession as exemplified by the procedures used in the 1994 Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota (Jaakko Pöyry Consulting, Inc. 1992, 1994).

As noted earlier, the FACCS was initially developed to project forest harvest residue availability. That included projections of carbon stock changes associated with the removal of tree tops and branches for energy production (Domke et al. 2008, Domke 2010). The model has since undergone several refinements. It was recognized early in development that using one year rather than multiple-year age classes in the change matrix improves the detail of output and simplifies the age class change matrix and associated estimated area represented by a particular forest type and age class. The current version cycles through the matrix one year (cell) at a time. The change algorithm has also been refined so that harvests can only occur in cells which have forest land area, thus eliminating spurious results (e.g., negative area estimates). Additionally, a graphic user interface was incorporated to allow the user to select various forest management scenarios compiled using the area change matrix generator. This feature incorporates thinning as an option, and by default retains a user-defined percentage of the total forest area in age classes above the rotation age. This and other management criteria can be modified interactively by the user, and through changes to various spreadsheet-based inputs to the tool.

The model was also developed so that basic forest inventory descriptions, harvesting plans, and utilization levels could be combined to estimate long-term harvest implications for both roundwood and residual biomass. Additionally, the model was designed to be accessible to a wide range of natural resource professionals familiar with spreadsheet software.

User interface

The FACCS model-user interface is an Excel workbook combined with a Visual Basic for Applications (VBA) Area Change Matrix Generator module. The model consists of a customized set of lookup tables which are populated with forest inventory information by forest type and stand age class (e.g., area, yield per-unit-area, harvest levels, rotation lengths, mortality) for the area of interest. Early versions of the FACCS used a user-defined harvest table to specify harvest rates to be applied to individual age classes over the planning period. Later versions incorporated a user specified annual harvest goal into VBA code activated through the Area Change Matrix Generator graphic user interface (GUI). Both harvesting methods populate a number of user-defined forest type sheets summarizing and detailing the progression of forested area through time under specified harvest conditions. Forest type sheets (e.g., change matrices and associated information overlays) rely on spreadsheet functions as well as models and data from the lookup table sheet to generate biomass estimates by area and age class over a user-defined time horizon. A variety of other information derived from the biomass estimates such as carbon stocks, biomass utilization, and decay of residuals can be generated in the forest type sheets, if desired. Results in each forest type sheet are summarized and linked to a single output sheet allowing the user to compare the results of specified harvest targets for the area of interest. The output sheet

utilizes a series of pivot-table tools to generate tables and figures describing the volume, biomass or carbon attributes of interest.

Data inputs

The FACCS model relies on a small number of core inputs which can be generated from existing forest inventory data or adapted from published sources. The model Version 1.3 was designed to operate using Forest Inventory Analysis (FIA) data summarized by forest type for the geographic region of interest. The primary model inputs include forest land area, biomass yield, and harvest level targets. Forest land area and related attributes can be estimated for specific geographic areas, political regions (i.e., counties and states), ownerships, or other attributes using spatial and relational database techniques in combination with the downloadable FIA database (FIA DataMart 2013, Miles 2011) or by using the online FIA EVALIDator Retrieval System (Miles 2013), other inventory systems or published sources. Forest land area information is then summarized by forest type and age class in a lookup table (Table 1) and linked to the appropriate forest type sheet. In practice, FIA 5-year age class tabulations can be used with simple division to provide starting one year age class distributions and age-dependent biomass yield.

Table 1. Forest type acreage by age class for Minnesota FIA Survey Units 1-3: 2004-2008¹.

| Age Class | White-red-jack pine | Spruce-fir | Oak-pine | Oak-hickory | Elm-ash-cottonwood | Maple-beech-birch | Aspen-birch |
|-----------|---------------------|------------|----------|-------------|--------------------|-------------------|-------------|
| 0-10 | 53,818 | 90,524 | 19,086 | 110,089 | 60,438 | 120,802 | 874,022 |
| 11-20 | 73,969 | 143,681 | 23,470 | 49,342 | 32,130 | 52,841 | 784,396 |
| 21-30 | 142,509 | 183,014 | 25,834 | 53,680 | 56,409 | 44,377 | 694,483 |
| 31-40 | 120,667 | 223,174 | 17,971 | 72,956 | 81,630 | 35,301 | 580,081 |
| 41-50 | 116,381 | 391,367 | 25,293 | 206,598 | 114,007 | 90,482 | 662,170 |
| 51-60 | 82,864 | 432,816 | 46,942 | 251,997 | 200,262 | 131,939 | 747,010 |
| 61-70 | 71,457 | 461,762 | 35,237 | 310,352 | 217,846 | 243,447 | 765,427 |
| 71-80 | 64,158 | 379,067 | 19,973 | 294,178 | 175,626 | 193,993 | 438,626 |
| 81-90 | 59,377 | 283,891 | 16,798 | 215,901 | 121,474 | 174,928 | 163,001 |
| 91-100 | 21,507 | 228,504 | 2,902 | 116,204 | 74,653 | 63,017 | 63,147 |
| 100+ | 33,838 | 641,271 | 17,062 | 127,407 | 132,952 | 66,105 | 49,012 |

¹ **Survey Unit 1:** Carlton, Cook, Koochiching, Lake, St. Louis, **Survey Unit 2:** Aitkin, Becker, Beltrami, Cass, Clearwater, Crow Wing, Hubbard, Itasca, Lake of the Woods, Mahnomen, Roseau, Wadena, **Survey Unit 3:** Anoka, Benton Carver, Chisago, Dakota, Douglas, Fillmore, Goodhue, Hennepin, Houston, Isanti, Kanabec, Le Sueur, Mille Lacs, Morrison, Olmsted, Otter Tail, Pine, Ramsey, Rice, Scott, Sherburne, St. Louis, Todd, Wabasha, Washington, Winona, Wright Counties.

In model usage to date, rotation length and harvest intensity have varied by forest type. Baseline rotation ages were taken from the *Forest Development Manual* (MnDNR 1997), and from pertinent Subsection Forest Resource Management Plans (SFRMPs–MnDNR 2010c), and adjusted by user experience and current harvesting conditions reported in the *Minnesota's Forest Resources* reports (MnDNR 2006b, 2007a, 2008). Subsequently, acres were harvested in each eligible (at or beyond rotation age) age class. The amount harvested was based on the volume (of that forest type) harvested annually statewide (as reported in the *Minnesota's Forest Resources* reports (MnDNR 2006b, 2007a, 2008, 2009, 2010d, 2011, 2012)). This harvest was then

proportioned by age class per an inspection of recent FIA harvest rates by age class (i.e., harvest rates varied by age class; not all acres were harvested at the rotation age).

In FACCS, harvesting continues throughout all harvestable age classes until all available stands are harvested or die. The model does not break covertime volume apart by tree species, but that is easy to implement given the percentage of volume by species from the initial inventory by covertime.

Biomass yield information can be generated in a similar manner on a per unit area basis by forest type and age class for the user-defined area or attribute of interest (e.g., site index class). Additionally, simple linear interpolation or more complex regression techniques can be employed to smooth these data where needed and thereby establish reasonable estimates for all age classes in the model. This is especially helpful when there is little data for one or more forest type and age class assignments. The biomass models developed for each forest type are included in the lookup table and linked to individual age classes in the forest type sheets for obtaining estimates of biomass yield. Alternatively, published biomass models (Jenkins et al. 2003, Woodall et al. 2012, Domke et al. 2012) may be used to obtain estimates by forest type if available inventory information does not include yield estimates. Further, published biomass models can be refitted to the variable of interest for a specific geographic region. Estimates of biomass per unit area in each forest type sheet are then multiplied by the estimated area harvested for that age class to generate biomass estimates by forest type and age class for the area of interest.

Harvest level targets in the model are based on FIA average statewide harvest levels by forest type. Harvest level targets at smaller spatial scales are proportionally adjusted, based on the area and volume subject to harvesting within a study area. As part of the model input, Table 2 summarizes Minnesota statewide harvest level targets based on 10-year average harvest levels published by the MnDNR (2009). Additional information such as mortality factors, residual biomass proportions, and management alternatives (e.g., shortened or extended rotations, early stand treatments, and thinnings) can also be incorporated, if desired.

Table 2. Harvest level targets by forest type based on the 10-year average statewide harvest levels in Minnesota (Becker et al. 2011).

| Forest Type | Proportion of statewide harvest | Estimated harvest (cords) | ODT/cord | Estimated ODT |
|---------------------|---------------------------------|---------------------------|----------|------------------|
| White-red/jack pine | 0.123 | 433,337 | 1.158 | 501,631 |
| Spruce/fir | 0.129 | 455,342 | 1.116 | 508,300 |
| Oak/pine | 0.008 | 27,532 | 1.259 | 34,671 |
| Oak/hickory | 0.037 | 132,354 | 1.375 | 181,987 |
| Elm/ash/cottonwood | 0.017 | 60,351 | 1.250 | 75,438 |
| Maple/beech/birch | 0.051 | 179,820 | 1.225 | 220,300 |
| Aspen/birch | 0.635 | 2,244,266 | 1.150 | 2,580,905 |
| TOTAL | 1.000 | 3,533,000 | | 4,103,232 |

Area change matrix

Each forest type sheet includes an area change matrix (Figure 1), which is populated with information from the lookup table sheet and driven by a series of spreadsheet functions and user-defined harvest rates. The change matrix within each forest type sheet consists of rows which represent time (years) and columns which represent individual forest type age classes (years). The function of this matrix is further illustrated in Table 3. The first row represents present day conditions (time = 0; labeled 2010) and is populated with an array of forest type area estimates for each individual age class from the lookup table sheet. In this simplified example, the forest type in year 2010 occupies 100 acres; all located in the year 1 age class. The total number of rows in the change matrix determines how long each forest type is grown. The modeled time horizon (growing period) in the example in Table 3 is 10 years (2010 to 2019). In FACCS Version 1.3 growing periods (rows) and age classes (columns) range to 120 years. Both the number of growing periods and the number of age classes can be adjusted to suit specific analytical needs. The first column (age class = 1) in the change matrix serves as the starting point for all acres removed from other cells due to harvesting and natural mortality.

In the example in Table 3, five acres were harvested in 2013 in age class 4 and were reset to the first column, where they immediately begin growing. As area is harvested over time, new cells are populated in the change matrix and multiple values will return to the first column at individual years. This is evident at years 2016 through 2019 in the example in Table 3.

Table 3. A simplified example of the age class change matrix within each forest type sheet.

| Year | Forest type age class (years) | | | | | | | | | | Total Area (acres) |
|------|-------------------------------|-----|-----|----|----|----|----|----|----|----|--------------------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 2010 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| 2011 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| 2012 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| 2013 | 5 | 0 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| 2014 | 0 | 5 | 0 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 100 |
| 2015 | 0 | 0 | 5 | 0 | 0 | 95 | 0 | 0 | 0 | 0 | 100 |
| 2016 | 6 | 0 | 0 | 4 | 0 | 0 | 90 | 0 | 0 | 0 | 100 |
| 2017 | 0 | 6 | 0 | 0 | 4 | 0 | 0 | 90 | 0 | 0 | 100 |
| 2018 | 0 | 0 | 6 | 0 | 0 | 4 | 0 | 0 | 90 | 0 | 100 |
| 2019 | 7 | 0 | 0 | 5 | 0 | 0 | 3 | 0 | 0 | 85 | 100 |

In the base model, the basic function cycling the area estimates from one age class to the next over time begins in the second row and column of the change matrix and continues throughout all cells. The basic function cycles area estimates from one cell (year and age class) to the next, thereby growing the area over time. In this example, cell 2010:1 represents 100 acres in year 2010 in age class 1. The basic function moves the value in cell 2010:1 to cell 2011:2 and so on through the matrix until a harvest occurs or the value reaches the end of the growing period in

| FOREST TYPE | | | | | | | | | | | | | | | | | | | | | |
|-------------------------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Variables | Age Class | | | | | | | | | | | | | | | | | | | | |
| | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 |
| MORTALITY FACTOR | 0.0011 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 |
| AREA (HECTARES) | 1,715 | 2,151 | 2,151 | 2,151 | 2,151 | 2,151 | 2,919 | 2,919 | 2,919 | 2,919 | 2,919 | 2,408 | 2,408 | 2,408 | 2,408 | 2,408 | 1,890 | 1,890 | 1,890 | 1,890 | 1,890 |
| BOLEWOOD (Mg - PREDICT) | 77.19 | 77.25 | 77.30 | 77.35 | 77.39 | 77.43 | 77.46 | 77.49 | 77.51 | 77.53 | 77.55 | 77.56 | 77.57 | 77.58 | 77.59 | 77.60 | 77.61 | 77.62 | 77.62 | 77.63 | 77.63 |
| STUMPS (Mg - PREDICT) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOPS AND LIMBS (Mg - PREDICT) | 17.32 | 17.33 | 17.34 | 17.35 | 17.36 | 17.36 | 17.37 | 17.37 | 17.38 | 17.38 | 17.38 | 17.39 | 17.39 | 17.39 | 17.39 | 17.39 | 17.39 | 17.40 | 17.40 | 17.40 | 17.40 |
| ROTATION AGE | 60 | | | | | | | | | | | | | | | | | | | | |
| Year | 2069 | 2070 | 2071 | 2072 | 2073 | 2074 | 2075 | 2076 | 2077 | 2078 | 2079 | 2080 | 2081 | 2082 | 2083 | 2084 | 2085 | 2086 | 2087 | 2088 | 2089 |
| | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 |
| 2010 | 1,715 | 2,151 | 2,151 | 2,151 | 2,151 | 2,151 | 2,919 | 2,919 | 2,919 | 2,919 | 2,919 | 2,408 | 2,408 | 2,408 | 2,408 | 2,408 | 1,890 | 1,890 | 1,890 | 1,890 | 1,890 |
| 2011 | 1,714 | 1,714 | 2,148 | 2,148 | 2,148 | 2,148 | 2,148 | 2,915 | 2,915 | 2,915 | 2,915 | 2,915 | 2,405 | 2,405 | 2,405 | 2,405 | 2,405 | 1,888 | 1,888 | 1,888 | 1,888 |
| 2012 | 1,712 | 1,712 | 1,711 | 2,145 | 2,145 | 2,145 | 2,145 | 2,145 | 2,910 | 2,910 | 2,910 | 2,910 | 2,912 | 2,403 | 2,403 | 2,403 | 2,403 | 2,403 | 1,886 | 1,886 | 1,886 |
| 2013 | 1,710 | 1,710 | 1,709 | 1,709 | 2,141 | 2,141 | 2,141 | 2,141 | 2,141 | 2,906 | 2,906 | 2,906 | 2,908 | 2,909 | 2,401 | 2,401 | 2,401 | 2,401 | 2,401 | 1,884 | 1,884 |
| 2014 | 1,708 | 1,708 | 1,707 | 1,707 | 1,706 | 2,138 | 2,138 | 2,138 | 2,138 | 2,902 | 2,902 | 2,903 | 2,905 | 2,906 | 2,398 | 2,398 | 2,398 | 2,398 | 2,398 | 2,398 | 1,882 |
| 2015 | 4,027 | 1,706 | 1,706 | 1,705 | 1,704 | 1,704 | 2,135 | 2,135 | 2,135 | 2,135 | 2,135 | 2,898 | 2,899 | 2,900 | 2,902 | 2,903 | 2,396 | 2,396 | 2,396 | 2,396 | 2,396 |
| 2016 | 4,023 | 4,023 | 1,704 | 1,703 | 1,702 | 1,702 | 1,701 | 2,132 | 2,132 | 2,132 | 2,132 | 2,132 | 2,132 | 2,896 | 2,896 | 2,898 | 2,899 | 2,900 | 2,393 | 2,393 | 2,393 |
| 2017 | 4,018 | 4,018 | 4,017 | 1,701 | 1,701 | 1,700 | 1,699 | 1,698 | 2,129 | 2,129 | 2,129 | 2,129 | 2,130 | 2,892 | 2,893 | 2,895 | 2,896 | 2,898 | 2,391 | 2,391 | 1,650 |
| 2018 | 4,014 | 4,014 | 4,012 | 4,011 | 1,699 | 1,698 | 1,697 | 1,697 | 1,696 | 2,126 | 2,126 | 2,126 | 2,127 | 2,128 | 2,889 | 2,890 | 2,892 | 2,893 | 2,368 | 698 | 683 |
| 2019 | 4,010 | 4,010 | 4,008 | 4,006 | 4,005 | 1,696 | 1,696 | 1,695 | 1,694 | 1,693 | 2,123 | 2,123 | 2,124 | 2,125 | 2,126 | 2,886 | 2,888 | 2,797 | 717 | 700 | 697 |
| 2020 | 3,814 | 4,006 | 4,004 | 4,002 | 4,001 | 3,999 | 1,694 | 1,693 | 1,692 | 1,692 | 1,691 | 2,119 | 2,120 | 2,121 | 2,123 | 2,124 | 2,883 | 2,048 | 715 | 716 | 699 |
| 2021 | 3,811 | 3,810 | 4,000 | 3,998 | 3,996 | 3,995 | 3,993 | 1,691 | 1,691 | 1,690 | 1,689 | 1,688 | 2,117 | 2,118 | 2,119 | 2,120 | 2,121 | 1,498 | 716 | 714 | 715 |
| 2022 | 3,808 | 3,807 | 3,804 | 3,994 | 3,992 | 3,990 | 3,989 | 3,987 | 1,689 | 1,688 | 1,687 | 1,687 | 1,687 | 2,115 | 2,116 | 2,117 | 1,445 | 733 | 718 | 715 | 714 |
| 2023 | 3,804 | 3,803 | 3,801 | 3,798 | 3,988 | 3,986 | 3,985 | 3,983 | 3,981 | 1,686 | 1,686 | 1,685 | 1,685 | 1,685 | 2,113 | 2,114 | 1,003 | 736 | 733 | 718 | 715 |
| 2024 | 3,801 | 3,800 | 3,798 | 3,795 | 3,793 | 3,982 | 3,980 | 3,979 | 3,977 | 3,975 | 1,684 | 1,683 | 1,683 | 1,683 | 1,683 | 1,917 | 752 | 737 | 735 | 732 | 717 |
| 2025 | 5,322 | 3,797 | 3,795 | 3,792 | 3,790 | 3,787 | 3,976 | 3,974 | 3,973 | 3,971 | 3,969 | 1,439 | 824 | 807 | 787 | 770 | 754 | 736 | 719 | 701 | 731 |
| 2026 | 5,318 | 5,316 | 3,792 | 3,789 | 3,787 | 3,784 | 3,782 | 3,970 | 3,969 | 3,967 | 2,855 | 840 | 822 | 807 | 789 | 772 | 754 | 737 | 719 | 718 | 700 |
| 2027 | 5,313 | 5,312 | 5,308 | 3,786 | 3,784 | 3,781 | 3,779 | 3,776 | 3,964 | 3,963 | 1,133 | 838 | 824 | 807 | 790 | 772 | 754 | 737 | 719 | 701 | 717 |
| 2028 | 5,309 | 5,307 | 5,304 | 5,301 | 3,780 | 3,778 | 3,775 | 3,773 | 3,770 | 2,510 | 855 | 842 | 824 | 807 | 790 | 772 | 754 | 737 | 718 | 701 | 701 |
| 2029 | 5,304 | 5,303 | 5,300 | 5,296 | 5,293 | 3,775 | 3,772 | 3,770 | 3,752 | 873 | 857 | 841 | 824 | 807 | 789 | 772 | 754 | 737 | 719 | 702 | 700 |
| 2030 | 5,014 | 5,299 | 5,295 | 5,292 | 5,288 | 5,285 | 3,769 | 3,767 | 2,085 | 877 | 858 | 842 | 824 | 807 | 790 | 772 | 754 | 737 | 719 | 702 | 701 |
| 2031 | 5,011 | 5,008 | 5,291 | 5,287 | 5,284 | 5,281 | 5,277 | 3,305 | 888 | 875 | 860 | 842 | 824 | 807 | 790 | 772 | 754 | 737 | 720 | 702 | 701 |
| 2032 | 5,008 | 5,006 | 5,001 | 5,283 | 5,280 | 5,276 | 5,273 | 3,140 | 891 | 876 | 859 | 841 | 824 | 807 | 790 | 772 | 754 | 737 | 720 | 702 | 701 |
| 2033 | 5,005 | 5,003 | 4,998 | 4,994 | 5,275 | 5,272 | 5,268 | 2,980 | 891 | 877 | 859 | 841 | 824 | 807 | 789 | 771 | 754 | 737 | 719 | 702 | 701 |
| 2034 | 5,002 | 5,000 | 4,995 | 4,991 | 4,986 | 5,268 | 5,264 | 3,083 | 893 | 877 | 858 | 842 | 825 | 806 | 790 | 772 | 754 | 737 | 720 | 702 | 701 |
| 2035 | 4,471 | 4,997 | 4,992 | 4,988 | 4,983 | 4,979 | 5,260 | 3,185 | 893 | 877 | 860 | 842 | 824 | 806 | 789 | 772 | 754 | 736 | 720 | 702 | 701 |
| 2036 | 4,469 | 4,467 | 4,989 | 4,985 | 4,981 | 4,976 | 4,972 | 3,288 | 891 | 877 | 858 | 841 | 824 | 807 | 789 | 771 | 754 | 737 | 720 | 702 | 701 |
| 2037 | 4,466 | 4,464 | 4,460 | 4,982 | 4,978 | 4,973 | 4,969 | 3,098 | 893 | 877 | 858 | 842 | 824 | 807 | 788 | 771 | 754 | 737 | 719 | 702 | 701 |

Figure 1: A screen-capture from a sample change matrix worksheet. The screen shows a tabulation of all hectares as they grow from one age class to the next. The effect of harvesting can be seen in the lower right quadrant of the worksheet where harvesting at a level approximating the long-term sustained yield has reduced timberland area above the rotation age to a level corresponding to 10% mature forest retention. Forest type specific biomass estimates by age, class resulting from the yield equations, are shown in the area above the change matrix.

the matrix. The basic function is linked to the harvest rate table in the lookup table sheet, allowing the user to harvest a percentage of forest type area in a particular age class (say based on specified forest management guidelines). In the example in Table 3, 5 percent of the area (five acres) in age class 4 was harvested in 2013 and returned to the first column to begin growing again. The percent harvested in each age class is dependent on the harvest target and the area available for harvest. The harvesting function is wrapped in a conditional expression so that only available area can be harvested, preventing negative values in the model and maintaining a fixed area in each row over time. The total area column in this example is the sum of all area across age classes for the year of interest. This column serves as a guide to ensure the matrix is functioning properly as a closed system, with no change in total area from year to year, despite harvesting.

In the change matrix generator version of FACCS, the logic used to cycle forest area from one age class to the next comes from a nested series of “For Next” statements written as part of a macro within Excel using VBA programming. These For Next loops, and associated logic, manipulate a series of data arrays used to track the progression of forest area, harvested area/volume, mortality, thinned area/volume, and other factors of interest through time. Harvests are accomplished iteratively, taking a small portion (0.10 percent) of the available area from an age class until either the harvest goal is met, or the age class is fully harvested (Appendix 2). As before, all area subject to harvest and/or mortality is moved back to the first age class to begin growing again.

Biomass estimation

Biomass estimates (e.g., for roundwood, tops and limbs, etc.) and other user-defined attributes are developed from the area change matrix. Harvested biomass is broken into two groups within the forest type sheets—roundwood and residual (e.g. tops and limbs). The average annual roundwood biomass harvest estimates are used to inform the user-defined harvest rates in the lookup table sheet. The residual material is estimated either as a proportion of the roundwood biomass with a percentage of that material being deemed extractable (MnDNR 2007), or via a separate biomass model developed from FIA or other available data for the area of interest.

Model assumptions

The FACCS model relies on several important assumptions:

- 1) Forest type area is fixed with no conversion to other types or additions or losses due to land use change.
- 2) Mortality is incorporated in the yields determined by age class.
- 3) Acres continue to age unless harvested or they reach advanced ages (at which time the model imposes mortality and these acres return to the youngest age class.
- 4) Forest type area estimates can be estimated for the area of interest by age class (as shown in Table 1).
- 5) Yield information is available or can be developed from data available for the area of interest for each forest type and age class.

- 6) Harvest information is available or can be developed from data available for the area of interest, and
- 7) Harvest targets used in the model are based on recent harvested volume estimates from the area of interest (Table 2).

In FACCS Version 1.3, the proportion of extractable biomass from harvest residues for each forest type was calculated from the volumes reported in the *Logged Area Residue Analysis* (MnDNR 2006a). Because the categories were broad, professional judgment was used to assign weights based on the *Timber Scaling Manual* (MnDNR 2007b).

Model Process and Tables—Steps For Using FACCS

The process outlined in Figure 2 is intended to describe the steps needed to successfully develop and run FACCS Version 1.3. Note that FACCS is not a point and click tool. Thus the process should be viewed as an example of how someone with a background in forest management and spreadsheet applications might adapt the basic principles embodied in the model to specific forest management scenarios. Model application will, of necessity, require the user to develop several tables summarizing or estimating: 1) local forest conditions, 2) harvest targets, 3) rotation age, 4) management scenarios, and 5) other factors of interest.

Step 1: Basic Input Preparation

Preliminary input tables can typically be generated from available FIA, DNR, or other local data sets (as described above), and form the basis for model estimates. A list of variables needed to run the model includes:

- a) Yield models describing the biomass per unit area produced by a given forest type at different ages within the area of interest.
- b) Estimated area of each forest type by age class within the study area (Table 1 in the FACCS).
- c) Estimates of total annual harvest volumes for the study area (Table 2 in the FACCS).
- d) Estimated proportion of the total harvest made up by each species (Table 3 in FACCS).
- e) Estimated annual volume and/or biomass harvested from each forest type (Table 4 in FACCS), or a proposed harvest target.
- f) Age factor inputs (Table 6 in the FACCS) used to move forest type acres from one age-class to the next (may include mortality estimates from FIA or other data) (e.g., What proportion of each age class moves to the next each year for each forest type? What proportion dies and returns to age-class zero?).
- g) Rotation length and other age-factor inputs (Table 7 in FACCS) are incorporated into the logic of the change matrix, and are used to help define the management scenarios summarized in the Harvest Target Inputs table.

- h) In early versions of the FACCS, the Harvest Target Inputs table (Table 8) was used to define a management scenario for each forest type and age class. Forest type and age-class specific harvest target inputs are based on typical rotation lengths and project specific management objectives. Values entered into this table represent a fraction of total forest type area to be harvested for each age class. These values must be adjusted by the user to either match existing harvest information by forest type and age class or to project harvest practices over some specified planning period. Rotation length (Table 7 in the FACCS) and an annual harvest volume target (Table 4 in the FACCS) were used in this example. The Harvest Target Inputs table can also be adjusted to incorporate early intermediate treatments.
- i) Additional inputs such as proportion of residual biomass to be utilized, decay rates, and other variables may be needed for specific applications. These variables are not a part of FACCS Version 1.3 and numerous non-trivial user specific changes may have to be made to accommodate them.

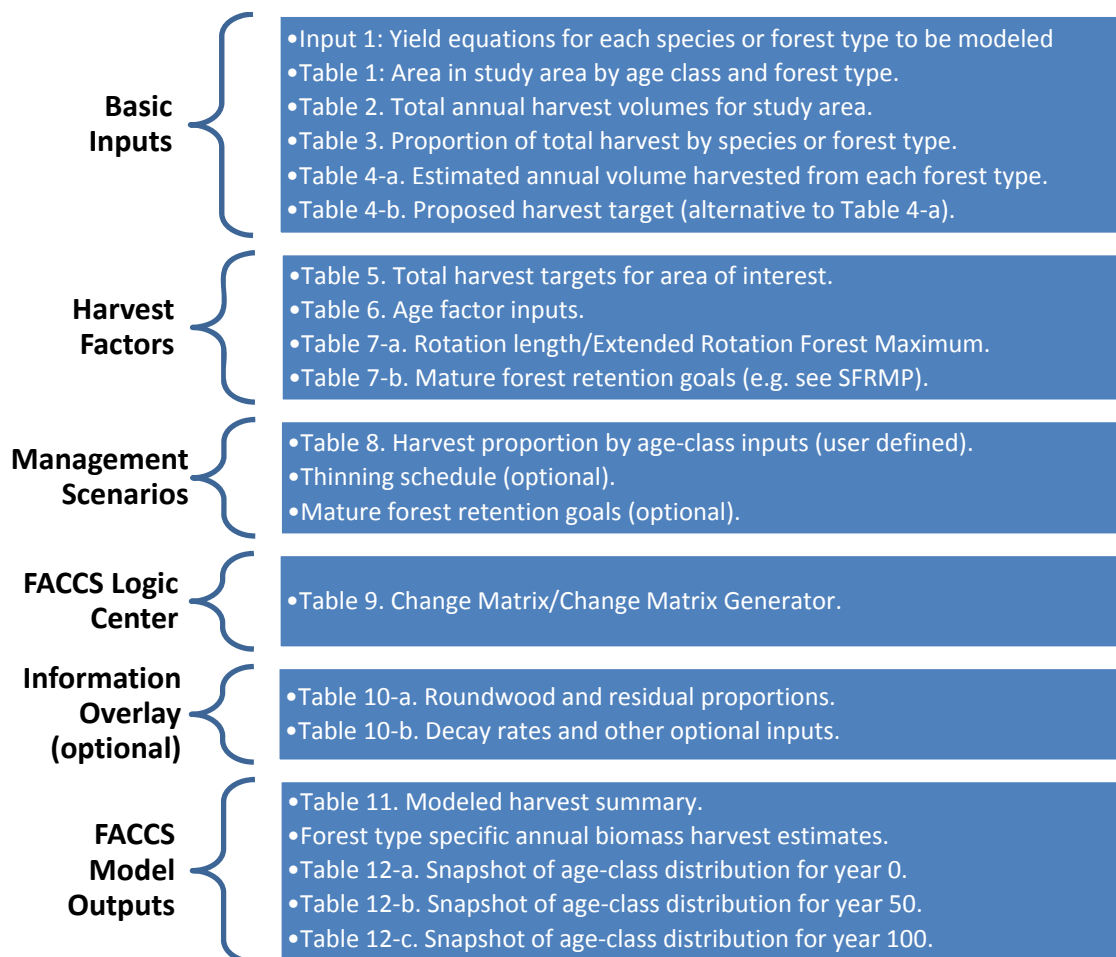


Figure 2: FACCS process with associated data tables and inputs used in the Excel formulation. Table numbers refer to tables in FACCS Version 1.3 except that Visual Basic code and management scenarios (both user defined and preprogrammed) replace Table 8.

Step 2: Adapt Model Parameters

- a) Adapt change matrices (Table 9 in the FACCS) and summary tables to accommodate project specific inputs (e.g. forest types, age-classes, planning period, and variables of interest).
- b) Adapt Harvest Target Inputs Table (Table 8 in the FACCS model). In practice, trial and error can be used to distribute harvest rates around most frequently documented rotation lengths.
- c) Overlay other data required to develop project specific outputs. The base model presented here used roundwood and residual proportions (Table 10 in the FACCS model) for estimation of available biomass.

Step 3: Review Outputs—Tables 11 to 12 in the FACCS

This is where knowing the model from the inside out is important. The user will need to know when something is not working based on their expected results.

Step 4: Adjust Harvest Target Inputs Table—Table 8 in the FACCS

Management scenarios can be adjusted further to fine-tune the timing and proportion of harvests from each age class and forest type. Model outputs should always be compared to initial harvest targets. Large variations in model output from initial values indicate an error in the process. In many cases, adjustment of the harvest rates and timing contained in the Harvest Target Inputs table can be used to tweak the model into compliance with targets.

Step 5: Repeat steps 2 to 4 as needed to achieve confidence in results.

FACCS Output

1. Modeled Harvest Summary (Table 11 in the FACCS)
Annual and cumulative harvested area for each forest type is shown for each year modeled. These data can be averaged across a specified time period, and/or graphed (Figure 3) to view harvest trends over time. The FACCS should produce output for which the sum of all harvested forest types and age-class portions closely approximates the initial harvest target. More detailed information for each forest type can be obtained from the individual forest type Change Matrix and Summary Output sheets.
2. Output Summary for 0, 50, and 100 years (Tables 12a-c in the FACCS)
Values in these tables represent total area in each forest type for 10-year age classes at times 0, 50, and 100 years. A graph of these three data series over time should show the distribution of harvested area recentering around the target harvest rotation age (Figure 4).

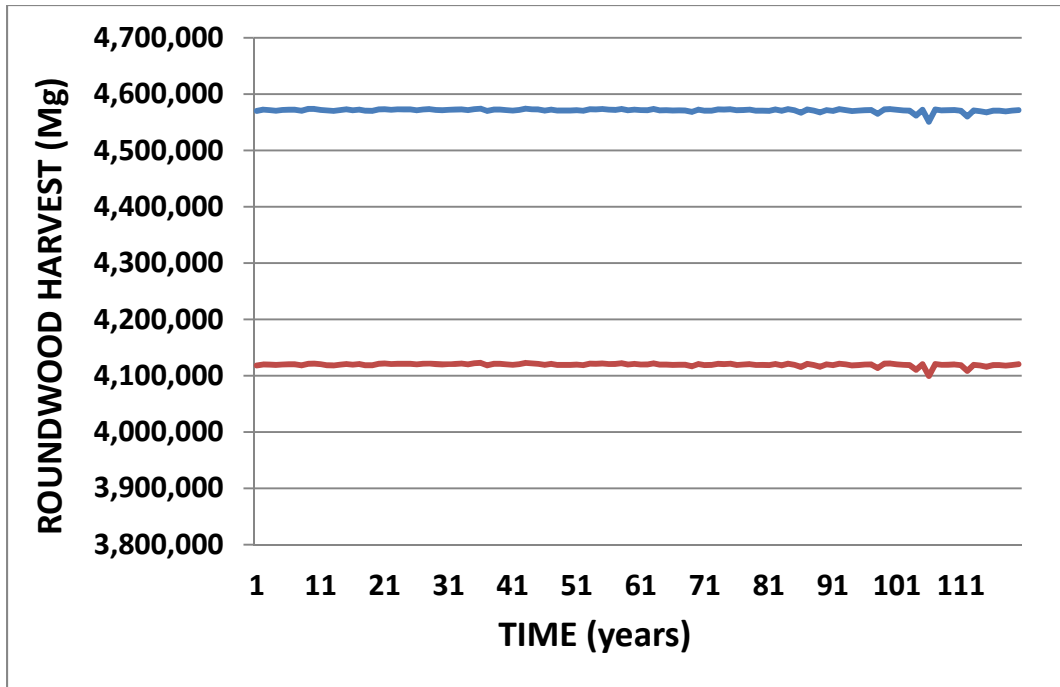


Figure 3: Potential roundwood harvests for all forest types in Minnesota’s Laurentian Mixed Forest Province. The upper blue line includes volume from thinning while the lower red line is the volume harvested without thinning. Results as estimated by the Change Matrix Generator version of FACCS shown above. Although this version of FACCS attempts to maintain a level harvest, modeled removals approaching or slightly exceeding the estimated long-term sustained yield (4,281,000 Mg or 3,974,000 Cords) may result in declining harvest volume as harvesting activities are pushed into age classes below the biological rotation age.

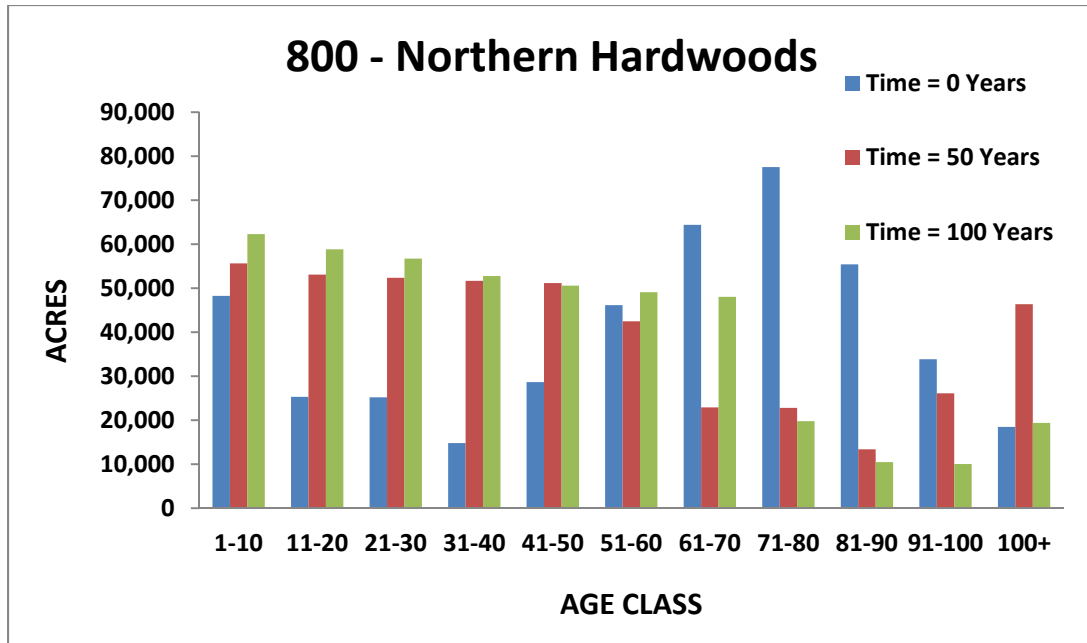


Figure 4: A snapshot of the age class distribution resulting from modeled harvests. These results are for the Northern Hardwoods forest type in Minnesota’s Laurentian Mixed Forest Province at a harvest level approaching the long-term sustained yield.

Model Applications

(1) Assessment of carbon flows with the utilization of harvest residues for energy

The FACCS was originally conceived to estimate residual biomass availability and the carbon flows associated with the procurement, transport and utilization of that material for a specific energy production project (Domke et al. 2008a). Additionally, once the FACCS base was developed to estimate residual biomass available within the study area, it was expanded further to estimate biomass decay rates (and associated CO₂ emissions) if the material were left in the forest rather than utilized for energy. It also estimated carbon sequestration of living biomass and carbon stocks of harvest residuals. Harvest and transport CO₂ emissions were also incorporated into the base model so carbon emissions with and without utilization for energy could be compared. These early expansions of the base model maintained the overall integrity of the FACCS interface with a lookup table sheet, several forest type sheets, a transport and harvest sheet, and an output sheet.

(2) Assessing forestation opportunities for carbon sequestration in Minnesota

The FACCS base model interface was adapted in a variety of ways in this study to accommodate the research needs. The goal of the project was to assess, under a variety of incentives, the carbon sequestration potential of forests on land that is currently in some alternative land use (Turner et al. 2010). The base model interface was changed so that the information originally in forest type sheets was housed within county-specific sheets with multiple change matrices for the different forest types within each county. Soil productivity information for each county was also

incorporated into the computational model and biomass models. Since the land under consideration was under some nonforest land use, all forest type area was phased into the model over a 10-year period to estimate actual establishment conditions (e.g., due to limitations in available planting stock, labor considerations, and managing competing vegetation). Finally, a carbon conversion matrix was developed and incorporated into the model to track carbon losses or gains associated with the conversion of nonforest area to different forest types.

(3) Outlook for forest biomass availability in Minnesota

The FACCS was adapted in this project to estimate residual biomass availability under a variety of management, utilization, marketing, and demand scenarios (Becker et al. 2010). The base model was expanded over five spreadsheet workbooks, one for each major ownership type considered in the study (federal, state, county, industrial private, and nonindustrial private). Each workbook included a series of lookup tables linked to individual county sheets from Minnesota and Wisconsin. Within each county-level sheet, seven area change matrices were built with accompanying biomass estimation tables which accommodated the wide array of management and utilization scenarios. Results from each sheet were linked to a single output sheet in each of the five ownership workbooks. An additional workbook was established to combine the output from the five ownership workbooks for use in developing tables and figures for reporting.

(4) Integration with ArcGIS Network Analyst for biomass supply analysis

The Microsoft Access version of the FIA database (FIA DataMart Version 5.1, USDA Forest Service 2012a) was used in conjunction with GIS analytical tools to develop spatially explicit estimates of forest type area and age distribution for input to the FACCS model. The FACCS provided estimates of future bolewood and residual biomass harvests within biomass procurement zones based on transportation distance from a central biomass energy facility. Average haul distance and transportation costs were also calculated based on the network distance between forested FIA plots and the central facility. These estimates were then used to inform decision making related to the development of new biomass energy facilities in Northeastern Minnesota (Becker, Wilson, and Ek *in progress*, Miller et al. 2013).

(5) Iterative harvesting/level harvest algorithm development to generate area change

Because of difficulties associated with using the FACCS model to estimate harvestable biomass over a long time horizon (100+ years) using a consistently applied annual harvest goal, it became necessary to modify the harvesting approach used to generate values in the area change matrix. These modifications were made using Visual Basic programming within Microsoft Excel®. The resulting area change matrix generator works similarly to earlier versions of the FACCS, except for changes in how the harvesting is carried out. The new area change matrix generator harvests iteratively, repeatedly taking a small portion of the area from a given age class until the annual harvest goal is met. Age classes above the extended rotation forest maximum age (ERFMax) are harvested first, followed by a selection of up to 20 age-classes between rotation age and ERFMax. The harvesting routine continues until either the harvest goal is met, or all selected age classes have been harvested. The selection process identifies age classes within the given range containing the most area. These age classes are then tagged for harvest, and forwarded to the harvesting algorithm. If the harvest goal cannot be met through normal harvesting, FACCS will

begin harvesting up to 30 percent of available area from age classes below the rotation age until the volumetric goal is met, or all age classes down to the minimum age for thinning (20 years) have been depleted. This approach allows the user to determine if a given harvest goal is sustainable over a long period of time. If the goal is set too high, later harvests may begin taking progressively more area from age classes below the rotation age to meet the volume target. When the harvest goal is sustainable, the goal will be met throughout the time horizon of interest without significant regeneration harvests occurring below the rotation age.

The Area Change Matrix Generator dynamically assembles a change matrix for each forest type based on annual harvest goals, rotation-age, mature forest retention goals, selected thins, and forest area inputs for each age class and forest type group. This new procedure allows for a 10 percent increase in the annual harvest goal by thinning up to 33 percent of the volume from existing stands without regenerating the affected area, and simulates the choices a forester might make in meeting wood production goals while managing the age class distribution.

A deflationary factor, $\lambda(t)$, inversely proportionate to the time since thinning is used to help estimate the volume deficit on recently thinned stands (Equation 1):

$$\lambda(t) = 1 - 0.975[1 - 1/(t - t_0 + 1)], \quad (1)$$

where t_0 equals the cycle number at the time of thinning, and t equals the current annual cycle of the model. This deflationary factor is modeled after the deflationary term used by Buckman et al. (2006) to track the declining variability in DBH distribution for thinned stands over time. A thin penalty is then calculated by multiplying this deflationary factor by the proportion of an age class which has been thinned, the proportion of material removed by thinning (33 percent), and then dividing by the quantity $e^{\text{CumulativeGrowthProportionSinceThin}}$ (Figure 5). In total, this thin penalty is designed to mimic the increased growth response of a stand to thinning, returning the stand to a fully stocked state after several cycles. Thinning will increase total cumulative yield while providing additional benefits to stand quality, vigor, and growth capacity.

Mature forest retention is achieved through the application of logic limiting the harvest of older age classes to levels which will retain a user-defined proportion of area above the rotation age. The logic involves a 2-step process, harvesting more heavily from age classes above ERFMax, then less heavily for age classes between ERFMax and Rotation age. The equation

$$\text{RetainedArea} = [(2 * \text{AverageMatureForest}) - (2 * \text{AverageMatureForest} * ((x - (\text{RotationAge})) / ((\text{AgeClasses} - 1) - (\text{RotationAge}))))],$$

where $\text{AverageMatureForest}$ equals the average area that should be present in mature age classes, is used to achieve the desired distribution of mature forest. The remaining terms are used to create a decreasing retention factor as we move farther beyond the rotation-age. This equation is used to set a lower limit on the area to be retained in mature age classes. While a lower limit is set on the amount of area remaining in mature age classes, no upper limit is explicitly set. Thus, the achievement of a desired age class distribution will depend on harvesting sufficient volume

to limit area entering mature age classes to the desired level. At lower levels of harvesting, additional area will accumulate in older age classes.

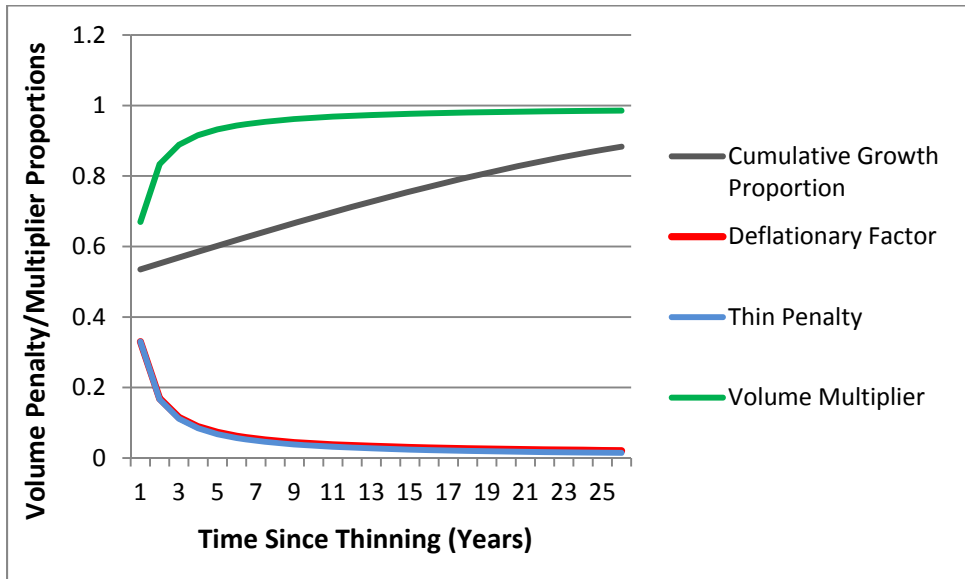


Figure 5: The 25-year distribution of variables used in calculating a deflating thin penalty. A volume multiplier calculated as $(1 - \text{ThinPenalty})$ is used to model the return to full stocking after a thin. Cumulative growth proportion for the Oak/Hickory forest type group is shown following a modeled thinning at age 60 years. Data shown assume 100 percent thinning of the modeled cohort.

These modifications allow a specified proportion (default = 10 percent) of total forested area to reach old-age (assuming a sustainable harvest goal is used), and will mimic approaches used by many forest managers to reduce the peaks and troughs in harvestable wood that becomes available over time.

Software Availability

The FACCS Version 1.3 in its spreadsheet form, including various input parameters and sample data can be downloaded from the Interagency Information Cooperative website (<http://iic.umn.edu/>). Links to versions of the model described here are listed on the “Growth Models for Managed Stands” page in the Recent Projects and Reports section of the site.

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Appendix 1. Glossary

Biomass—Organic materials produced by plants, such as leaves, roots, seeds, and stalks. In the case of this study, biomass was considered tree tops and limbs left following a roundwood harvesting operation along with small diameter stems less than 4 inches in diameter at breast height.

Chip—Small piece of woody material that can be used to manufacture pulp/paper and engineered wood products, fuel for power/heat generation, and landscape cover/soil amendment.

CO₂e—Describes how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO₂) as the reference. The atomic weight of oxygen (O) is ca. 16 and the atomic weight of carbon (C) is ca. 12 so the conversion factor from C to CO₂e is $(12+16*2)/12$ or 3.67.

Cord—Common unit of measure for roundwood delivered to a forest products facility. One standard cord is a stacked pile approximately 4 feet x 4 feet x 8 feet in size containing 128 cubic feet of wood, air and bark. A cord contains approximately 79 cubic feet of wood (minus airspace and bark) and approximately 92 cubic feet of wood and bark.

M—Is the SI prefix used to represent mega or 10⁶ which is equivalent to 1 million.

Megawatt—One thousand kilowatts. Enough electricity to support approximately 750 to 1,000 households.

MWh—One megawatt hour. 10,000 lbs of steam will generate 1 megawatt hour of electricity.

Methanotroph—Soil bacteria that use methane as their only source of carbon and energy for growth and development.

Moisture content—The amount of moisture contained in woody material. Typically expressed as a percentage of total weight.

Oven dry ton (ODT)—Wood weight at zero percent moisture content.

Roundwood—Logs, bolts, or other round sections cut from the bole of trees, typically in lengths of 8 feet or greater.

Tonne—Metric unit of mass equivalent to 1,000 kilograms or ca. 2,205 lbs.

Short ton—A unit of mass equivalent to 2,000 lbs or ca. 907 kilograms.

Appendix 2. Code for Iterative Harvest Algorithm

```
' Each Year, increment the harvest for the current age class until the goal is met
' or area is reduced to the old-age retention goal.
'If it has been more than 5 years since thinning, then harvest.
If arThinYear(y - 1, x - 1) < (y - 5) Then
  For Z = 1 To 999
    If RemainingArea > ((2 * AverageOldForest) - (2 * AverageOldForest * ((x -
      (RotationAge)) / ((AgeClasses - 1) - (RotationAge)))))) Then
      If Val(HarvestedIncrement) < Val(AreaXY) Then
        If Val(HarvestVol) < (Val(HarvestGoal)) Then
          HarvestedIncrement = 2 * (Val(AreaXY) * 0.001)
          HarvestedXY = HarvestedXY + HarvestedIncrement
          Harvested = Harvested + HarvestedIncrement
          HarvestVolXY = HarvestedXY * arYieldCurveBole(1, x - 1) * (1 -
            (arThinPenalty(y - 1, x - 1)))
          HarvestVol = HarvestVol + (HarvestedIncrement *
            arYieldCurveBole(1, x - 1)) * (1 - (arThinPenalty(y - 1, x - 1)))
          Z = Z + 1
          HarvestRate = Z * (0.001)
          RemainingArea = RemainingArea - HarvestedIncrement
        End If
      End If
    End If
  Next
End If
```

Where:

y = Model year or cycle number,

x = Age class, and

AreaXY = Area in a given age class.