Carbon Sequestration and the Principia Forest:
Managing Forest Assets for Carbon Neutrality

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Abstract

Climate change is one of the defining issues of our time. Because institutions of higher learning play a prominent role in shaping the thought leaders of the 21st century, colleges and universities must take a leadership role in operationalizing values related to a more just and sustainable future. Forests sequester (store) carbon in their biomass through photosynthesis, thereby helping to offset anthropogenic increases in atmospheric carbon dioxide (CO_2) that are causing global climate change. The rate of carbon sequestration across a forest ecosystem depends on the growth regimes of constituent tree species, conditions of growth where the tree is planted, and density of tree wood. Sequestration is greatest in younger life stages when the tree is metabolizing and growing at its fastest rate. By including carbon sequestration as one component of an integrated management plan that may also include academic research, biodiversity conservation, and recreation, the Principia Forest can be a positive asset in Principia College's strategic goal of carbon neutrality.

The USDA Forest Vegetation Simulator (FVS) was used to estimate the total amount of carbon dioxide equivalent (eCO_2) sequestered by the 809-hectare (2000-acre) Principia Forest on a yearly basis. Results were compared with total annual emissions from the college enterprise in order to evaluate the role the forest is currently playing in our carbon neutrality equation. My research shows that in the near term (2015-2025), the forest is sequestering, annually, 131.6% of our total emissions, rendering the college carbon neutral based on its direct assets. Importantly, my research also suggests that if the college is to remain committed to carbon neutrality, we have less than ten years to significantly rein in our emissions (attributed in largest part to our use of natural gas), institute proactive forestry management regimes that optimize carbon sequestration (such as selective low-impact harvesting, Amur honeysuckle removal, and native forest restoration), and explore the potential for carbon sequestration by grasslands and hill prairies.

Simulations using tree stand data collected from the Principia Forest demonstrate that without proactive management, sequestration declines well below emissions levels in the near term (by 2026 or 2027). This is most likely associated with the increasing average age of the forest and a relatively low recruitment of young trees in the dense understory of invasive Amur honeysuckle. In contrast, simulations that incorporated proactive management designed to produce the strongest model for sequestering carbon showed an immediate decrease in carbon sequestration rate after a thinning event; however, annual sequestration rates increase over time in the context of a younger, faster growing forest stand age structure – and ultimately return (perhaps by 2055) to levels able to offset college emissions (assuming 2014 emissions levels) through the end of the century.

Among my recommendations are that a complete analysis of carbon sequestration be conducted to look at root productivity, soil respiration, and tree ring analysis in order to better understand carbon inputs and outputs within the Principia Forest. Regular greenhouse gas emissions inventories should be conducted for the college enterprise, and forest carbon inventories using the latest simulation tools (this field is rapidly evolving) should be compared with emissions data to ensure that the built environment is as energy-efficient as possible and that the Principia Forest is managed to optimize its role in carbon offsetting. Research is also needed to quantify the role of prairie eco-systems in storing carbon and contributing positively to the campus's carbon budget. Finally, urgent action is needed to significantly reduce the biomass of invasive Amur honeysuckle, with an aim to both safeguard the integrity of the natural forest and increase the carbon storage metabolism of the Principia Forest over time.

Introduction

Rising levels of atmospheric carbon dioxide (CO_2) indicate a global carbon cycle[1] in which more carbon is being released into the atmosphere than is being absorbed by natural carbon sinks (IPCC 2014, Sedjo 1992). Forests play a dominant role in the terrestrial carbon cycle by sequestering (storing) carbon in the biomass of trees (Bascietto et al. 2004). Sedjo (1992) estimated that forests contain 86% of above ground carbon and 73% of total soil carbon. More recently, Wanga et al. (2014) estimated that forests sequester 2.0 - 3.4 Pg[2] of carbon per year on a global scale. Because trees act as a CO_2 "sink" by fixing carbon during photosynthesis (Nowak et al. 2013), forests are increasingly viewed as a natural way to mitigate increasing CO_2 levels in the atmosphere due to anthropogenic climate change (Bonan 2008, Smith et al. 2006). In Canada, for example, tree planting is targeted to sequester enough carbon to meet one-fifth of the nation's international climate change obligations, and at lower cost than emissions reduction (van Kooten et al. 2002).

The rate of carbon sequestration across a forest ecosystem depends on the growth characteristics of constituent tree species, conditions of growth where the tree is planted, and density of tree wood. Sequestration is greatest in younger growth stages when the tree is metabolizing and growing at its fastest rate. The amount of CO_2 sequestered in a certain tree can be estimated and then divided by the tree's age to estimate an annual sequestration rate. This sequestration rate, extrapolated across the forest, can be compared to an estimate of carbon emissions; for example, sequestration by the Principia Forest can be balanced with the estimated greenhouse gas emissions of Principia College to validate the college's progress toward the stated goal of carbon neutrality (Principia College 2014). Forestry practices (e.g., selecting for younger and/or faster growing trees) can be utilized, as desired, to optimize the potential for using the forest as an asset in reducing the amount of carbon emitted into the atmosphere as a result of human activities (Chazdon et al. 2016).

Climate change is one of the defining issues of our time (IPCC 2014, NAS 2014). Because institutions of higher learning play a prominent role in shaping the thought leaders of the 21st century, it is important that colleges and universities take a leadership role in operationalizing their values related to a more just and verdant future. There is also a positive economic component to taking a stand against climate change. Of nearly 700 signatories of the American College and University Presidents' Climate Commitment (ACUPCC), 82% have affirmed that their Climate Action Plan has saved their institution money (Second Nature 2014). Principia College has not yet signed the ACUPCC, but it has taken steps toward operationalizing its values related to sustainability, such as by developing an academic degree program in sustainability, gaining Forest Stewardship Council (FSC) certification[3] of forest practices, implementing single-stream recycling, and so on.

Principia College oversees large areas of forest that may be a hidden asset in the college's commitment to sustainability. To further evaluate this possibility, the specific objectives of my Sustainability Research Project were to estimate the total amount of carbon sequestered on a yearly basis by the Principia Forest, compare that to the college's estimated annual carbon emissions (data from

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[1] "The circulation of carbon between living organisms and their surroundings. Carbon dioxide from the atmosphere is synthesized by plants into plant tissue, which is ingested and metabolized by animals and converted to carbon dioxide again during respiration and decay." Source: http://www.thefreedictionary.com/carbon+cycle

[2] One petagram (Pg) of carbon dioxide is equivalent to one Metric Gigatonne (gt, or Giga)

[3] The FSC mission is "to promote environmentally sound, socially beneficial and economically prosperous management of the world's forests." Source: https://us.fsc.org/en-us/what-we-do/mission-and-vision

Eckert 2015), make recommendations regarding the benefits (or not) of incorporating carbon sequestration into management goals for the Principia Forest, and to gain a greater understanding of sustainability, specifically the role of forests and forest management in supporting the college's aspiration to be carbon neutral.

Site Description

Principia College is located in Elsah, IL, about 50 miles north of St. Louis, MO. The campus is comprised of some 1052 hectares (2600 acres) of land, including the 809-hectare (2000-acre) "Principia Forest", which consists primarily of mature oak hickory forest (Lovseth 2015). The forest is certified by the Forest Stewardship Council (FSC), which grants certification to entities that provide products from forests that are responsibly managed and provide environmental, social, and economical benefits.[4] The role that our FSC-certified forest plays – or could play – in offsetting carbon emissions attributed to the institution is the focus of this research report.

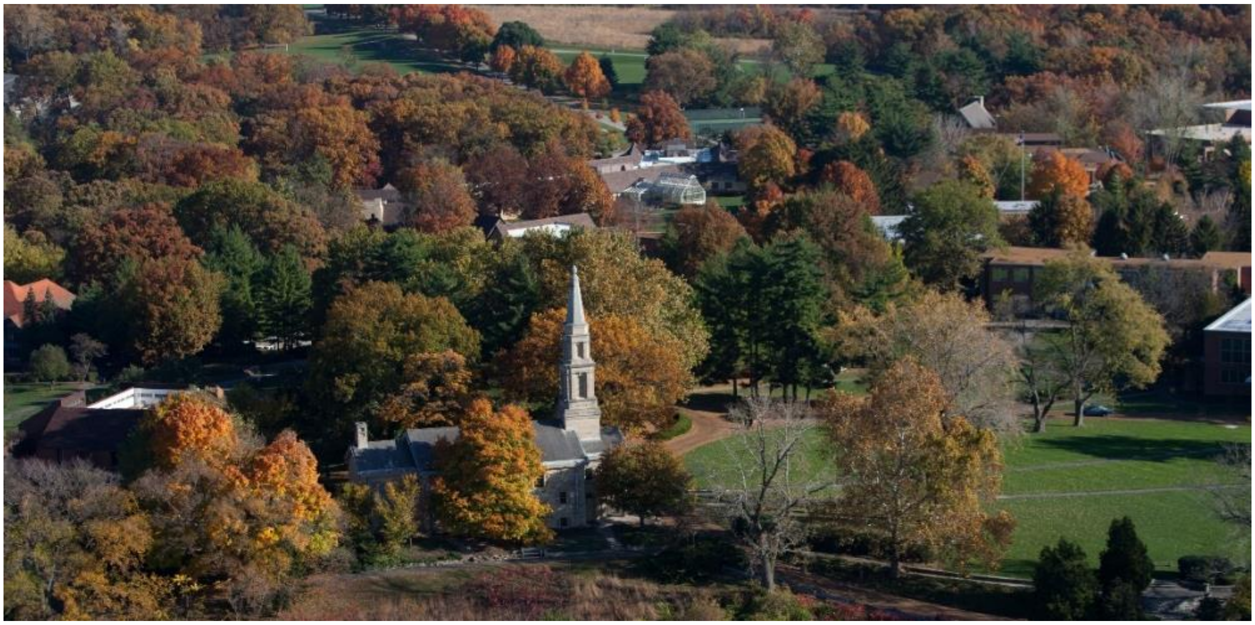

Figure 1. Principia College's iconic chapel is the heart of a 1052 hectare wooded campus dominated by the Principia Forest (809 hectares), but also featuring a core built environment, agricultural lands (including the chemical-free Three Rivers Community Farm), native prairie ecosystems, and freshwater habitats.

Methods

FVS Program

Following a comprehensive literature review, the USDA Forest Vegetation Simulator (FVS) was selected to calculate the total carbon sequestered by the Principia Forest. FVS is an individual tree,

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[4] "The Forest Stewardship Council sets standards for responsible forest management [and] harnesses market demand to ensure forests are responsibly managed." https://us.fsc.org/en-us/what-we-do

distance-independent growth model designed to predict changes in tree diameter, height, crown ratio, and crown width. Many reports related to carbon (e.g., snags, down dead wood, forest floor) are included in the FVS program's Fire and Fuels Extension (FFE) function (Hoover and Rebain 2011) (Appendix I) and it is for this reason, in addition to the FFE being designed to work at smaller, more localized scales, that it was chosen as the simulation platform for my study. I employed the use of GIS to help with the calculations and to provide spatial representations.

Once tree stand data is entered into the FVS/FFE program, various management methods can be simulated to manipulate the stand over a predetermined time interval. I used tree stand data from Tidwell (2016) – along with the Central States (CS) variant (Dixon and Keyser 2016) (Appendix II) – to best represent the Principia Forest as a whole. Raw tree data were entered into an Excel® spreadsheet and then imported directly into an Access® database provided by the USDA Forest Service.[5] Specific step-by-step directions to enter the data into a database, run a simulation in FVS, and view the outputs can be found in USDA Forest Service (2007).

FVS Simulation

In the simulation, different types of management practices are selected to visualize and evaluate effects. In this study, two simulations were run with two different outputs. The first simulation was run for 100 years (2015-2115) with no management intervention. This allowed the program to use allometric equations to produce an output describing carbon sequestration in a naturally occurring forest without any management.

The second simulation was run over an identical simulated time frame (2015-2115), but with selected management designed to produce the strongest model for sequestering carbon. Several simulations were run by selecting different management techniques designed to compare and contrast sequestration rates over the century 2015 to 2115. Specifically, the second simulation factored in a management regime defined by natural regeneration of yellow poplar (*Liriodendron tulipifera*), white oak (*Quercus alba*), and sugar maple (*Acer saccharum*) at every occurrence of a thinning event. These trees were selected as they tend to be fast growing and are native to the Principia Forest. The option "thin to a Q factor" was chosen where thinning occurred every 60 years, with every tree above a diameter at breast height (DBH) of 24 inches cut. This DBH was selected to favor smaller, more metabolically active (faster growing) trees able to sequester greater volumes of carbon, and it provided the most beneficial result in terms of carbon sequestration.

Annual Sequestration Rate

The average annual change in carbon stock was calculated by taking the difference between the carbon at specified time (Time 2) and a previous time (Time 1), and then dividing that difference by the number of intervening years to give a rate of change for that period of time. The FVS system has a default minimum of 10 years for predicting the total stand carbon, since anything under that time range may result in either an over-prediction or an under-prediction. To convert total carbon sequestered to its "carbon dioxide equivalent" (eCO_2), the mass of carbon was multiplied by 44/12, the molecular weight ratio of carbon dioxide to carbon, to represent the total amount sequestered in terms of eCO_2.

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[5] http://www.fs.fed.us/fmsc/fvs/index.shtml (FVS)

ArcMap® was used to determine whether plots with known tree data were located in areas where the age of the forest was known.

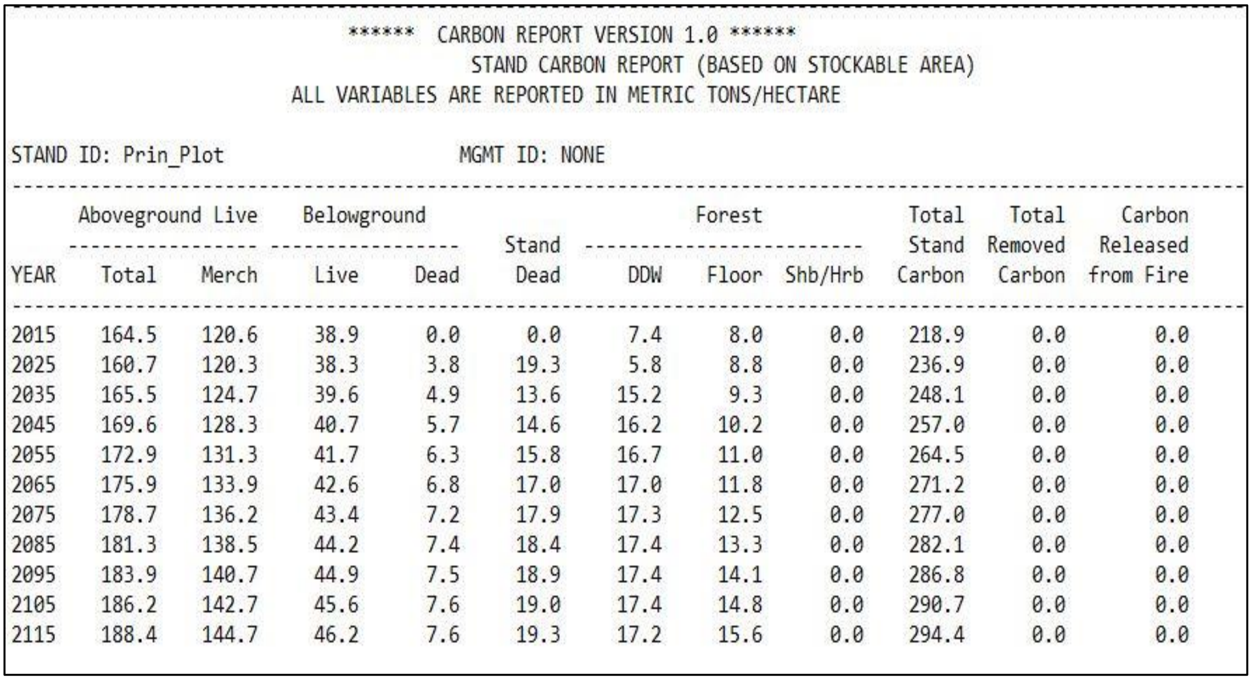
FVS Caveat

FVS has some programmatic limitations in tracking all sources of carbon inputs and outputs. First, the program was not designed originally for sequestration estimates. It was designed as a growth and yield model where the carbon report function takes the standard FVS outputs and converts it to biomass, which ultimately can be used to estimate total carbon. Second, it does not take into account all aspects of forest management, such as the emissions related to production, transportation, and application of fertilizer (Hoover and Rebain 2011). Fully understanding entity-wide carbon accounting is beyond the scope of this program, meaning, for example, that this report does not address carbon sequestration by native prairie or other habitat types on campus.

Results

The first simulation was run for 100 years (2015-2115) with no management intervention, and produced an output describing carbon sequestration in a naturally occurring forest (Table 1). This simulation indicated a total of 5339.4 metric tonnes (MT eCO_2) sequestered annually from 2015 to 2025, compared to an estimated 4055.9 MT eCO_2 emitted in 2014 by Principia College (Eckert 2015) (Figure 2). We also see that the sequestration *rate* declines over time (Figure 3); ultimately, without management intervention, sequestration cannot keep pace with college emissions under a business-as-usual scenario where emissions remain statistically constant (as they have been since 2009; Eckert 2015) at approximately 4000 MT eCO_2 (Figure 4).

Table 1. Carbon report with no management for the 100-year period 2015 – 2115.



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                              ******  CARBON REPORT VERSION 1.0 ******
                                         STAND CARBON REPORT (BASED ON STOCKABLE AREA)
                         ALL VARIABLES ARE REPORTED IN METRIC TONS/HECTARE

STAND ID: Prin_Plot                      MGMT ID: NONE
----------------------------------------------------------------------------------------------------
      Aboveground Live    Belowground                       Forest               Total   Total    Carbon
     ---------------- ----------------   Stand  ------------------------   Stand  Removed  Released
YEAR   Total    Merch      Live     Dead    Dead       DDW    Floor  Shb/Hrb   Carbon  Carbon  from Fire
----------------------------------------------------------------------------------------------------
2015   164.5    120.6      38.9      0.0     0.0       7.4      8.0      0.0    218.9     0.0        0.0
2025   160.7    120.3      38.3      3.8    19.3       5.8      8.8      0.0    236.9     0.0        0.0
2035   165.5    124.7      39.6      4.9    13.6      15.2      9.3      0.0    248.1     0.0        0.0
2045   169.6    128.3      40.7      5.7    14.6      16.2     10.2      0.0    257.0     0.0        0.0
2055   172.9    131.3      41.7      6.3    15.8      16.7     11.0      0.0    264.5     0.0        0.0
2065   175.9    133.9      42.6      6.8    17.0      17.0     11.8      0.0    271.2     0.0        0.0
2075   178.7    136.2      43.4      7.2    17.9      17.3     12.5      0.0    277.0     0.0        0.0
2085   181.3    138.5      44.2      7.4    18.4      17.4     13.3      0.0    282.1     0.0        0.0
2095   183.9    140.7      44.9      7.5    18.9      17.4     14.1      0.0    286.8     0.0        0.0
2105   186.2    142.7      45.6      7.6    19.0      17.4     14.8      0.0    290.7     0.0        0.0
2115   188.4    144.7      46.2      7.6    19.3      17.2     15.6      0.0    294.4     0.0        0.0
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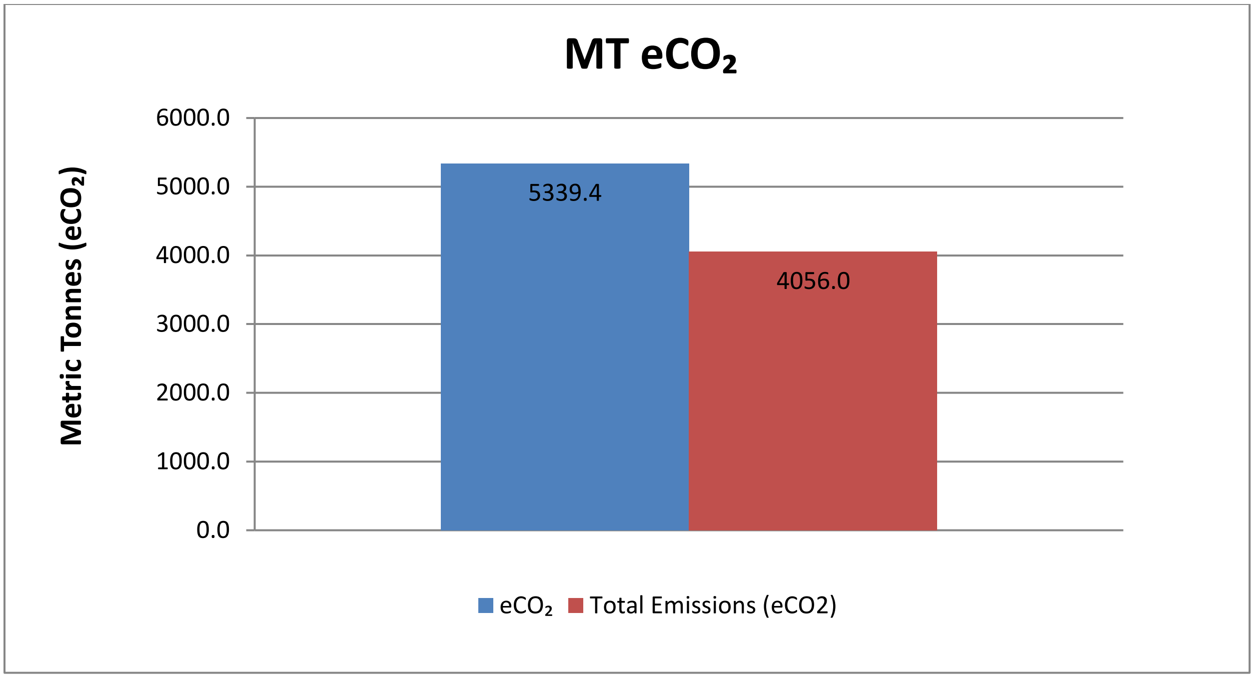


Figure 2. Total metric tonnes (MT) carbon dioxide equivalent (eCO_2) sequestered by the Principia Forest (estimated for the decade 2015-2025) compared to total eCO_2 emissions from Principia College in 2014 (Eckert 2015).

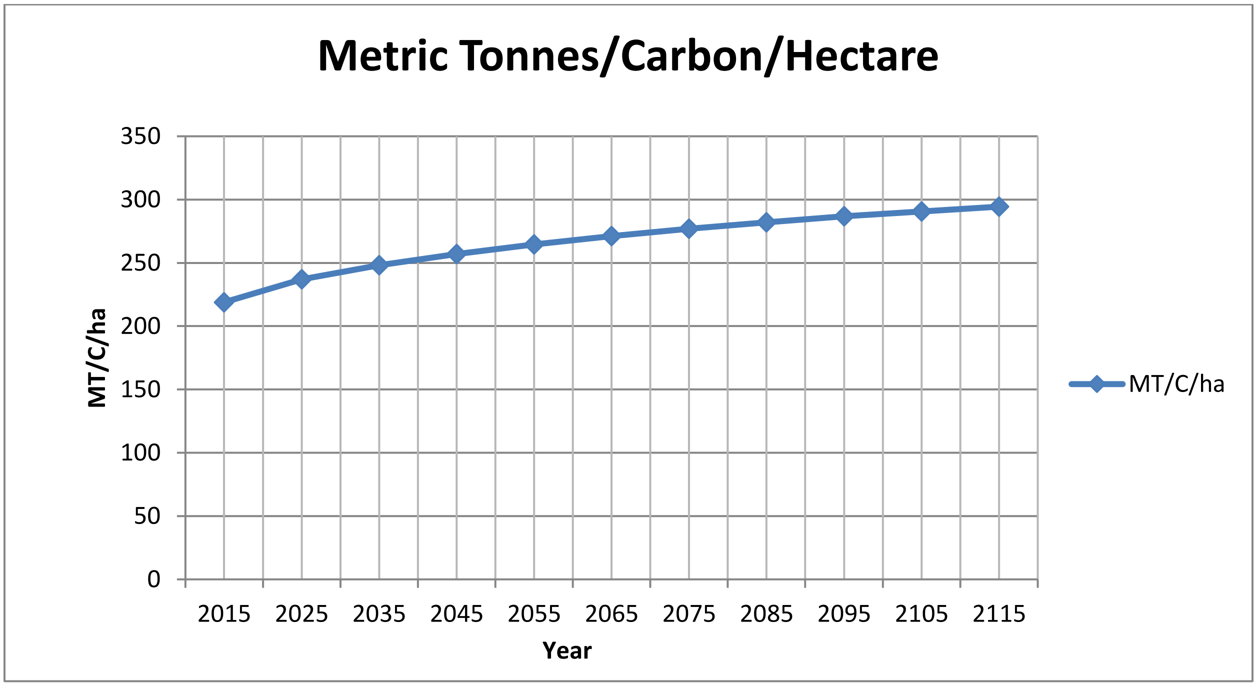


Figure 3. Total stand carbon (2015-2115), with sequestration *rate* declining over time. Total stand carbon for the Principia Forest was estimated from hectare plots where tree size, density, and biomass were known.

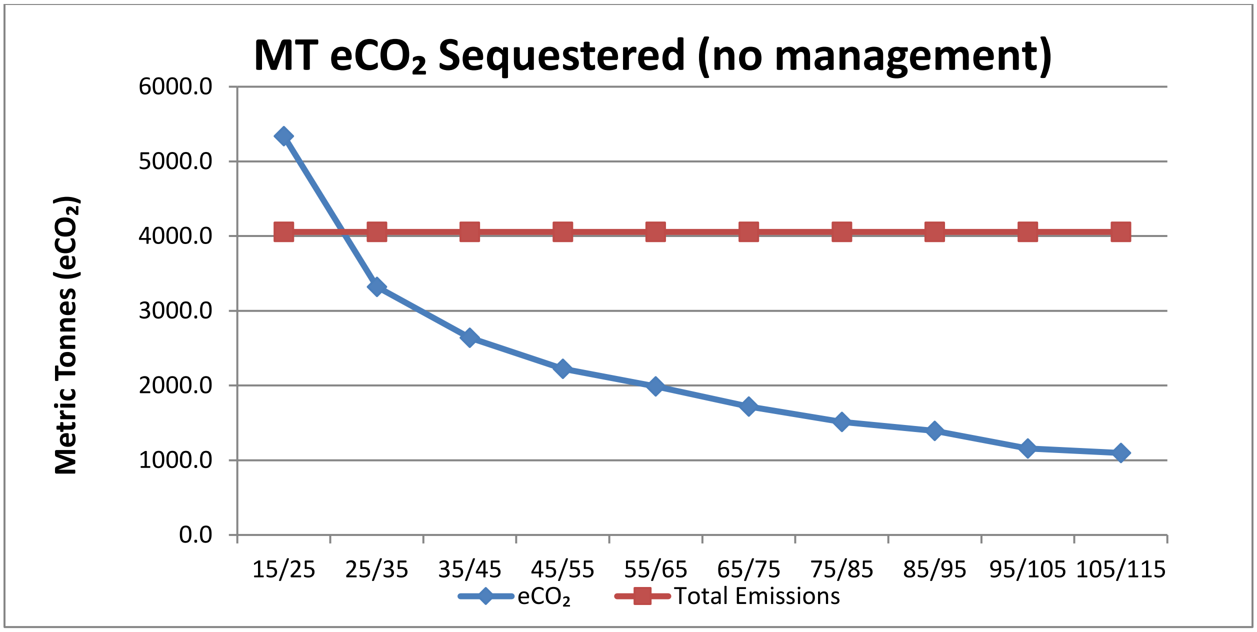
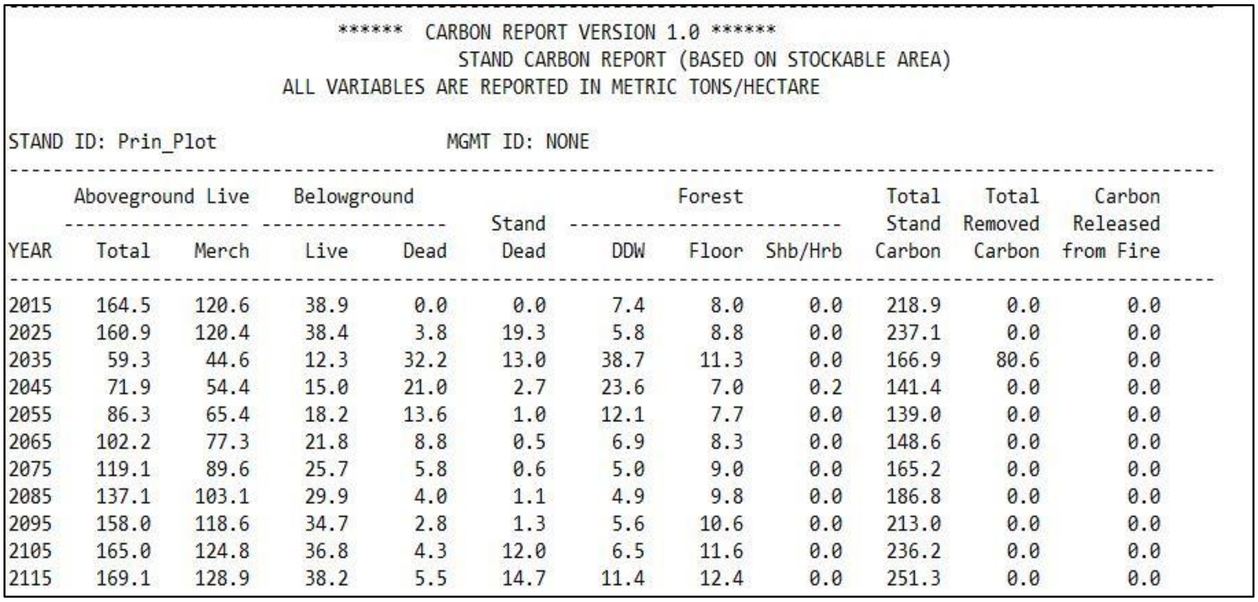


Figure 4. In the absence of management intervention, total metric tonnes (MT) carbon dioxide equivalent (eCO_2) sequestered by the Principia Forest declines over the course of a century. In contrast, carbon emissions, at least in the near term (projected from 2009-2014 data, Eckert 2015), remain statistically flat at approximately 4000 MT.

The second simulation was run over an identical time frame (2015-2115), but with selected management designed to produce the strongest model for sequestering carbon (Table 2). The results of the second simulation showed an immediate decrease in carbon sequestration rate after a thinning event; however, annual sequestration rates then increase over time in the context of a younger, faster growing forest stand age structure (Figure 5).

Table 2. Carbon report with a management regime of thinning to a Q-factor for the 100-year period 2015 – 2115.



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                                 ******  CARBON REPORT VERSION 1.0 ******
                                            STAND CARBON REPORT (BASED ON STOCKABLE AREA)
                              ALL VARIABLES ARE REPORTED IN METRIC TONS/HECTARE

STAND ID: Prin_Plot                         MGMT ID: NONE
-------------------------------------------------------------------------------------------------
      Aboveground Live     Belowground                   Forest               Total    Total      Carbon
     -----------------  -----------------  Stand  -------------------------  Stand   Removed   Released
YEAR    Total    Merch     Live     Dead    Dead      DDW    Floor  Shb/Hrb  Carbon   Carbon  from Fire
-------------------------------------------------------------------------------------------------
2015    164.5    120.6     38.9      0.0     0.0      7.4      8.0      0.0   218.9      0.0        0.0
2025    160.9    120.4     38.4      3.8    19.3      5.8      8.8      0.0   237.1      0.0        0.0
2035     59.3     44.6     12.3     32.2    13.0     38.7     11.3      0.0   166.9     80.6        0.0
2045     71.9     54.4     15.0     21.0     2.7     23.6      7.0      0.2   141.4      0.0        0.0
2055     86.3     65.4     18.2     13.6     1.0     12.1      7.7      0.0   139.0      0.0        0.0
2065    102.2     77.3     21.8      8.8     0.5      6.9      8.3      0.0   148.6      0.0        0.0
2075    119.1     89.6     25.7      5.8     0.6      5.0      9.0      0.0   165.2      0.0        0.0
2085    137.1    103.1     29.9      4.0     1.1      4.9      9.8      0.0   186.8      0.0        0.0
2095    158.0    118.6     34.7      2.8     1.3      5.6     10.6      0.0   213.0      0.0        0.0
2105    165.0    124.8     36.8      4.3    12.0      6.5     11.6      0.0   236.2      0.0        0.0
2115    169.1    128.9     38.2      5.5    14.7     11.4     12.4      0.0   251.3      0.0        0.0
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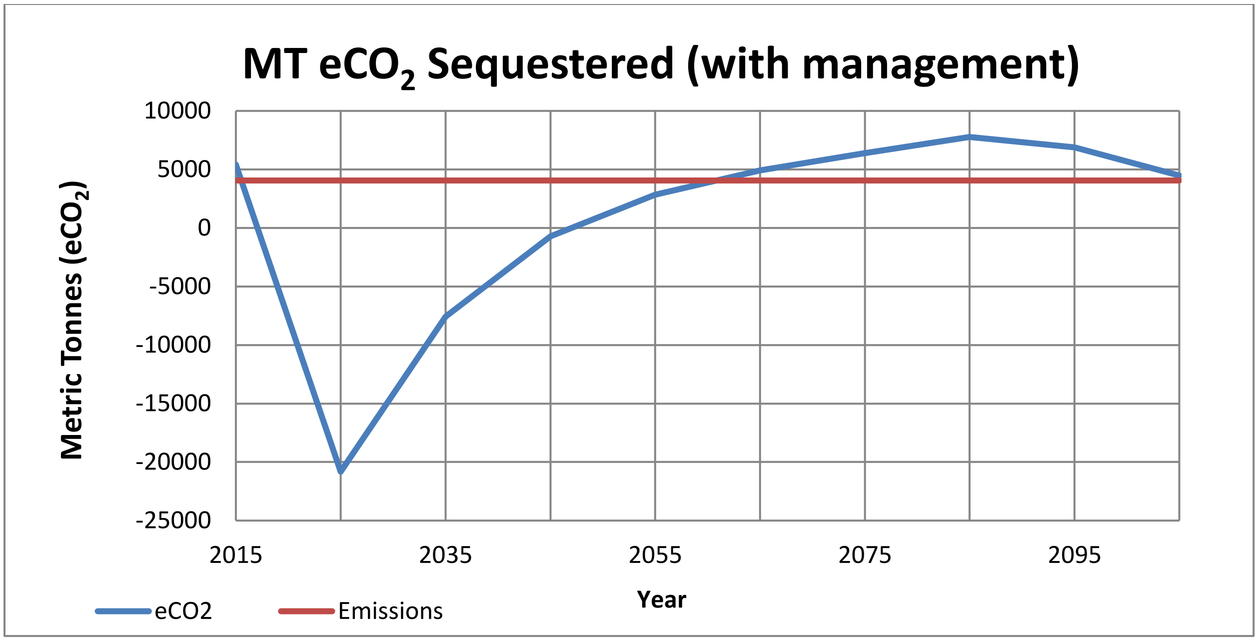

Figure 5. With active management (specifically, forest thinning in 2025 and thereafter at 30 year intervals resulting in natural regeneration of yellow poplar, white oak, and sugar maple), total metric tonnes (MT) carbon dioxide equivalent (eCO_2) sequestered by the Principia Forest (blue line) stabilizes at ca. 5000 MT for a half-century.

None of the research plots utilized in my study were located where forest stand age had been established (Figure 6); therefore, tree age did not play a factor in the simulations.

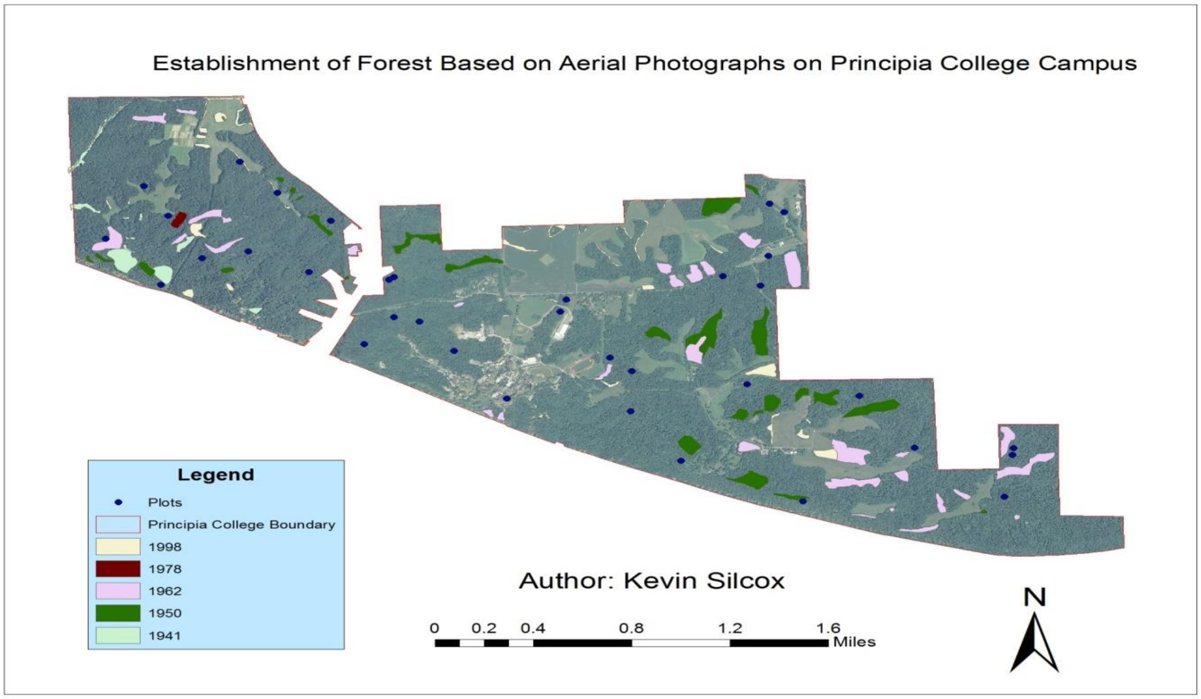

Figure 6. Map showing the Principia College boundary. Tidwell's (2016) thesis plots, which provided the raw data for my study, appear as blue dots. Aged stands are indicated by color. Trees established in 1941 are, today (2016) 75 years old, 1950 = 66 years old, 1962 = 54 years old, 1978 = 38 years old, and 1998 = 18 years old.

Discussion

Overview

The growing number of climate change agreements and action plans at scales ranging from local (e.g., City of St. Louis 2013) to national (e.g., Melillo et al. 2014) to global (e.g., UNFCCC 1992, Paris Agreement 2015) has led to a greater need for information on forest carbon stocks now and in the future (Hoover and Rebain 2011). In the U.S., it is estimated that forests absorb 10-20% of total U.S. greenhouse gas emissions, making them the country's single most important sink (Sample et al. 2015). Active land use management can play a critical role in ensuring that forests remain a net carbon sink (USDA Forest Service 2015). However, a 2010 study showed that the effectiveness of U.S. forests as a carbon sink is declining and that as early as 2030, U.S. forests may turn into a net source of greenhouse gases (Sample et al. 2015) due to deforestation and land conversion (Wear et al. 2013).

The role of forests in helping stabilize atmospheric CO_2 depends on harvest and disturbance rates, expectations of future forest productivity, and the ability to deploy management practices and technologies that enhance the amount of sequestered carbon. The forest sector includes a variety of activities that can increase carbon sequestration, such as afforestation, forest restoration, agroforestry, forest management, and urban forestry. These activities could increase the national carbon stocks by 100 to 200 Tg C/year and similar practices could increase the carbon stocks of the Principia Forest, as well. Using the right type of practice for site-specific goals is the key to success. Determining that "right type" is the biggest challenge in sustainable forestry, as a range of uncertainty in biological, ecological, and economic functions still surrounds forest management (Birdsey et al. 2006, Kumari 1996).

Forest composition also plays an important role in carbon sequestration, and the presence of invasive species (such as Amur honeysuckle, *Lonicera maackii*) can significantly complicate a management plan. Amur honeysuckle is an exotic invasive species that is rapidly expanding throughout the forests of Eastern North America. It forms a dense understory layer that alters tree regeneration, negatively effects the shrub layer diversity, and changes ecosystem function (Arthur et al. 2012). It causes the overall rate of mean radial basal area to be reduced by roughly 53%, which has a strong negative influence on the growth and productivity of canopy trees (Hartman and McCarthy 2007), thus reducing carbon sequestration.

In my study, management vs no management simulations showed promising signs of sustaining the forest, while at the same time increasing the amount of carbon sequestered over time. After modelling several simulations, a regime of harvesting older trees for their timber every 60 years and letting natural regeneration of younger, fast sequestering trees, showed the best results from a sustainability standpoint. Other forest management studies have shown success when the rotation age is extended and managers employ a type of harvesting (e.g., low impact harvesting, selective thinning) that retains a significant amount of above ground carbon stock at all times (Sample et al. 2015). Sustainable harvesting also contributes to financial targets when valuable forest products, including timber, are sold.

One Planet Principles

When thinking about sustainability, Bioregional's "One Planet Principles" often come to mind. The One Planet Principles are ten guiding principles designed to promote sustainability in ecology, economy and equity.[6] A sustainable community uses its resources to meet current needs, while ensuring that adequate resources will be available for future generations to meet *their* needs (WCED 1987).[7] When looking to become a sustainable society, these ten principles are an important aspect that can help guide the planning of that society.

Two of the ten principles apply directly to my project: Land Use and Wildlife, and Zero Carbon. Sustainable land use involves protecting and restoring biodiversity and natural habitats through best practices related to land use and management. Achieving a "zero carbon" future means that all buildings are energy-efficient and reliant on 100% renewable energy.[8] Sustainable forest management can be defined as the adoption of a management system such that the continuity of the ecosystem, including all of its goods and services, is non-declining over time (Kumari 1996). Sustainable forest management aids in sustainable land use, providing the basis for wildlife to prosper. Forests that sequester carbon can offset the carbon emissions of a campus (or city or nation) and can contribute to the strategic goal of carbon neutrality.

Principia College

The focus of my study was to compare the amount of carbon stored in the living biomass of trees comprising the 809-hectare Principia Forest to the amount of eCO_2 emitted by Principia College on an annual basis. To intensify the role that the forest plays in the college's carbon neutrality goal, my research suggests that active management toward younger, faster growing trees is needed. At the same time, the campus must rely less on carbon-based fuels, thereby reducing primary emissions (Eckert 2015).

Simulations using tree stand data collected from the Principia Forest demonstrate that, in the absence of management, sequestration rates decline well below emissions levels in the near term. This is most likely occurring due to the increasing average age of the forest, which is associated with reduced growth rates among mature trees (Sample et al. 2015). This ultimately leads to the older trees sequestering less carbon (compare to younger trees), since 50% of the tree is made of carbon. To redress this issue, a management plan that involves thinning, selective replanting, and natural regeneration is recommended. Standard elements of such a plan include nutrient management, residue management, thinning, utilization of products from thinning, low-impact harvesting, optimizing rotation length, species or genotype selection, and forest biotechnology (Birdsey et al. 2006). Bascietto et al. (2004) conclude that in the absence of carefully planned thinning practices, carbon uptake by the trees declines.

Forest ecosystems are diverse, and there is no "one size fits all" management plan to achieve optimal carbon sequestration at a particular site. My research aimed to estimate, using the USDA Forest Vegetation Simulator (FVS) tool, the total carbon sequestered annually by the 809-hectare Principia Forest – and then compare that to the college's greenhouse gas emissions (Eckert 2015)

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[6] http://www.bioregional.com/oneplanetliving/ (One Planet Principles)

[7] http://www.ala.org/srrt/tfoe/lbsc/librariesbuildsustainablecommunitiesthree (Three Dynamics of Sustainable Communities)

[8] http://www.bioregional.com/oneplanetliving/ (One Planet Living Principles)

in order to (i) make recommendations regarding the benefits (or not) of managing the Principia Forest for offsetting campus emissions, and (ii) gain a deeper understanding of sustainability, specifically the role of forests and forest management in mitigating the effects of climate change.

As noted in my Methods, two simulations, both modeled over the course of a century (2015-2115) – one with no management intervention, the other with a timbering rotation designed to produce the strongest model for sequestering carbon – were evaluated with respect to their ability to contribute to Principia College's strategic aim to be carbon neutral (Principia College 2014).

The first simulation indicated a total of 5339.4 metric tonnes (MT eCO_2) sequestered by the Principia Forest in 2014, compared to an estimated 4055.9 MT eCO_2 emitted by the college that year (Eckert 2015). However, without management intervention, the rate of sequestration declines over time as the forest ages and, eventually (perhaps by 2026 or 2027), it cannot keep pace with emissions under a business-as-usual scenario where the college's emissions remain statistically constant at approximately 4000 MT eCO_2 (which they have been since 2009; Eckert 2015).

The second simulation, also run from 2015 to 2115, incorporated selected management designed to produce the strongest model for sequestering carbon. The results show an immediate decrease in carbon sequestration rate after a thinning event; however, annual sequestration rates increase over time in the context of a younger, faster growing forest stand age structure – and ultimately return (perhaps by 2055) to levels sufficient to offset college emissions under a business-as-usual scenario where, again, emissions remain statistically constant at approximately 4000 MT eCO_2.

In summary, my research shows that in the near term (2015-2025), the Principia Forest sequesters, on an annual basis, 131.6% of the college's total emissions – rendering the college carbon neutral based on its direct assets. My research also suggests that if the college is to remain committed to carbon neutrality as a strategic goal, we have less than ten years to significantly rein in our emissions (attributed in largest part to our use of natural gas; see Eckert 2015), institute proactive forestry management regimes that optimize carbon sequestration, and explore the potential for sequestration by grasslands and hill prairies.

Further Recommendations

A complete analysis of carbon sequestration should be conducted to look at root productivity, soil respiration, and tree ring analysis in order to get a better understanding of the carbon inputs and outputs within the Principia Forest (Bacietto et al. 2004). Regular greenhouse gas emissions inventories (cf. Eckert 2015) should be conducted for the college enterprise, and associated forest carbon inventories using the latest simulation tools (this field is rapidly evolving) should be compared with these emissions data to ensure that the built environment is as energy-efficient as possible and that the Principia Forest is managed to optimize its role in carbon offsetting. Of course, the element of carbon sequestration is only one of many important management targets for the forest, including academic research, biodiversity conservation, and recreation.

Grasslands and hill prairies may also act as carbon sinks (Rigge et al. 2013). Perennial grasses store high amounts of organic carbon in the soil and their extensive fibrous root systems – with active microbial communities – provide an excellent mechanism for accumulating and storing carbon (Frank and Karn 2005). Further research is needed to quantify the role of prairie ecosystems in storing carbon and contributing positively to the campus's carbon budget.

Urgent action is needed to significantly reduce the biomass of invasive Amur honeysuckle, *Lonicera maackii*, with an aim to both safeguard the integrity of the natural forest and increase the carbon storage metabolism of the Principia Forest over time.

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Appendix I

Forest Carbon Estimation Using the Forest Vegetation Simulator: Seven Things You Need to Know

USDA (2011)

United States
Department of
Agriculture

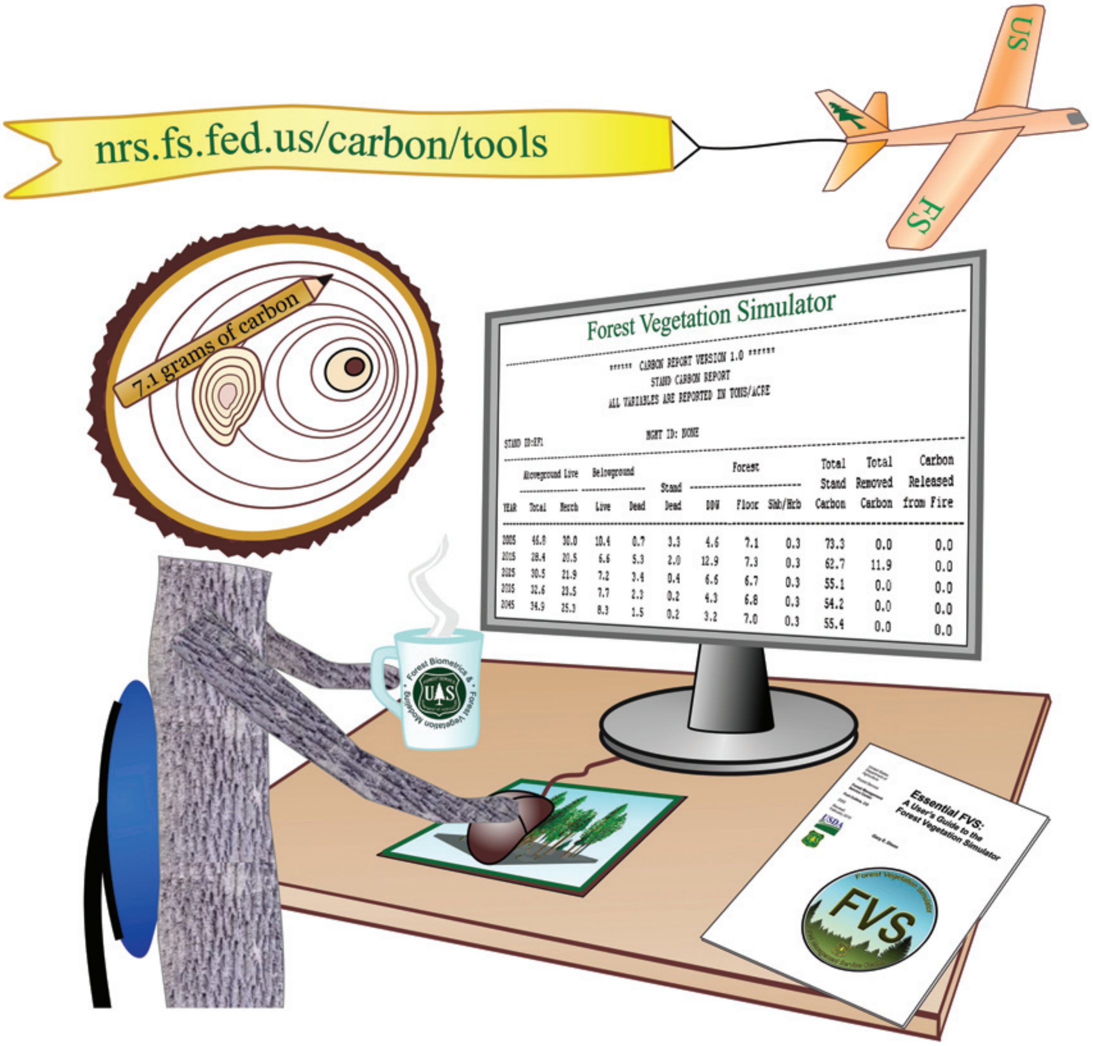
Forest
Service

**Northern
Research Station**

**General Technical
Report NRS-77**

FOREST CARBON ESTIMATION USING THE FOREST VEGETATION SIMULATOR: SEVEN THINGS YOU NEED TO KNOW

Coeli M. Hoover and Stephanie A. Rebain



```
****** CARBON REPORT VERSION 1.0 ******
STAND CARBON REPORT
ALL VARIABLES ARE REPORTED IN TONS/ACRE

STAND ID:EF1                MGMT ID: NONE
-----------------------------------------------------------------------------------
     Aboveground Live  Belowground              Forest            Total  Total    Carbon
     ---------------- ----------- Stand ---------------------    Stand  Removed  Released
YEAR  Total   Merch   Live   Dead  Dead   DDW   Floor  Shb/Hrb   Carbon  Carbon  from Fire
-----------------------------------------------------------------------------------
2005  46.8    30.0    10.4   0.7   3.3    4.6   7.1    0.3       73.3    0.0     0.0
2015  28.4    20.5    6.6    5.3   2.0    12.9  7.3    0.3       62.7    11.9    0.0
2025  30.5    21.9    7.2    3.4   0.4    6.6   6.7    0.3       55.1    0.0     0.0
2035  32.6    23.5    7.7    2.3   0.2    4.3   6.8    0.3       54.2    0.0     0.0
2045  34.9    25.3    8.3    1.5   0.2    3.2   7.0    0.3       55.4    0.0     0.0
```

Abstract

Interest in options for forest-related greenhouse gas mitigation is growing, and so is the need to assess the carbon implications of forest management actions. Generating estimates of key carbon pools can be time consuming and cumbersome, and exploring the carbon consequences of management alternatives is often a complicated task. In response to this, carbon reporting capability has been added to the Forest Vegetation Simulator (FVS) growth and yield modeling system, allowing users to produce carbon reports along with traditional FVS outputs. All methods and computations are consistent with Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance and U.S. voluntary carbon accounting rules and guidelines. We briefly describe the FVS system, outline the carbon pools estimated, and provide an overview of the data requirements, capabilities, features, and limitations of the model and the carbon reports. We also review common questions and pitfalls encountered by users when running the model.

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FVS Web site: http://www.fs.fed.us/fmsc/fvs/

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INTRODUCTION

The growing number of climate change agreements and action plans at scales ranging from local to international has led to a greater need for information on forest carbon stocks now and in the future. While estimates and tools (Proctor et al. 2005, Smith and Heath 2008, Smith et al. 2007, U.S. EPA 2008, http://nrs.fs.fed.us/carbon/tools) are available at the county, state, and national levels, developing carbon estimates from inventory data for multiple forest stands or entire forests is generally an unwieldy process. As forest carbon markets and greenhouse gas policies continue to develop, the question of how forest management practices positively or negatively affect carbon storage becomes increasingly important to answer. Accounting for carbon in harvested wood presents an additional challenge when addressing questions related to management options and carbon storage.

Because of this increased demand for forest carbon information, a tool was needed to calculate forest carbon stocks at smaller scales and to estimate forest management impacts on carbon. The following criteria were established: the tool should be accessible to managers, include the ability to assess the carbon consequences of forest management treatments, and produce estimates consistent with most current U.S. and international carbon accounting rules and guidelines. The FVS carbon reports were developed to meet this need. We provide here a brief overview of the FVS growth and yield framework, including data requirements; describe the FVS carbon reports and their underlying calculations; discuss their capabilities, strengths, limitations, and appropriate use; and list seven questions and answers important to know when working with FVS.

FOREST VEGETATION SIMULATOR (FVS) OVERVIEW

The Forest Vegetation Simulator (FVS) is the U.S. Forest Service's nationally supported framework for forest growth and yield modeling. At its core, FVS is an individual-tree, distance-independent growth model; it predicts changes in tree diameter, height, crown ratio, and crown width, as well as mortality, over time. FVS has both empirical and theoretical components. For instance, diameter growth is predicted from equations fit from large datasets collected in a particular geographic area. Conversely, in many of the FVS geographic variants, density-related mortality is predicted by comparing the current stand density to a theoretical maximum density for that stand type. FVS originated as the Stand Prognosis Model in the 1970s (Stage 1973, Wykoff et al. 1982) and, over time, growth equations developed for other parts of the United States were incorporated into the Prognosis framework. It has also been expanded to meet the needs of contemporary forest managers and is now a true stand dynamics model. Much of this expansion occurred through the addition of extensions to the core growth model. Extensions of FVS model impacts of various disturbance agents such as fire, insects, and disease, and they provide additional outputs such as economic analyses. As a result, model output pertains to a wide range of natural resource disciplines and includes variables related to stand density and structure, canopy cover, snag dynamics, fire hazard, and surface fuel loading, among others (see Appendix A for a partial listing of available FVS outputs). Users can also include standard forest management activities to see how they affect these forest attributes. Consequently, the FVS model is used extensively throughout the United States to support forest management decisionmaking; approximately 20 geographic variants, each with regionally appropriate default settings, are available (Crookston and Dixon 2005, Dixon 2002). A map and list of available FVS variants are provided in Appendix B.

FVS has specific input requirements and file formats. Input data may be stored in text files or within a database. Either way, a variety of site-specific data is input. Stand-level variables include a measure of site quality, such as site index or habitat type, slope, aspect, elevation, inventory design specifications, and other parameters (see Appendix C for a description of input variables). If these values are not provided, default values are used. Default values are also provided for forest floor and various diameter classes of down dead wood; users should enter their own data if available. Necessary tree-level variables include species and diameter. Additional variables such as tree status (live or dead), height, crown ratio, and others may be included; otherwise they will be estimated using default relationships. Each geographic variant has various submodels that describe growth and mortality; users should become familiar with the various model relationships and the input data requirements and structure, all of which are documented in publications on the FVS Web site.

The Fire and Fuels Extension (FFE)

Fire is a component of many forest ecosystems, and the Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003) was developed to provide managers with a way to assess the intensity and effects of potential fires and to model the effects of fuel management treatments on fire potential. Many components of stand-level carbon (e.g., snags, down dead wood, forest floor) are estimated and reported in the FFE, so carbon reporting functions are part of the FFE rather than a separate extension to the model system (for a detailed description of the development history, see Hoover and Rebain 2008). Calculation methods are consistent with the U.S. Carbon Accounting Rules and Guidelines for the 1605(b) Voluntary Greenhouse Gas Reporting Program (available at http://www.eia.doe.gov/oiaf/1605/gdlins.html) and the Intergovernmental Panel on Climate Change (IPCC; Penman et al. 2003) Good Practice Guidance for national greenhouse gas inventories. A complete description of the carbon reporting methods and assumptions is provided in the Fire and Fuels Extension documentation (Rebain 2010).

CARBON REPORTS: POOLS AND OPTIONS

Two carbon reports can be requested: the Stand Carbon Report and the Harvested Carbon Report. The Stand Carbon Report includes the major carbon pools as defined by the U.S. Carbon Accounting Rules and Guidelines and the IPCC Good Practice Guidance: aboveground live tree, belowground live tree (coarse roots), belowground dead tree, standing dead trees, down dead wood, forest floor, and understory (shrubs/herbs). In addition, the merchantable portion of live tree carbon is reported, as well as total stand carbon, total carbon removed during harvest, and carbon released from fire (if harvests or fires are simulated). Users may choose measurement units: pool amounts can be reported in tons per acre, metric tons per hectare, or metric tons per acre, a hybrid unit. Carbon stock estimates are produced by applying conversion factors to the biomass estimates generated as part of the standard calculations carried out by FVS and the FFE. Biomass, expressed as dry weight, is assumed to be 50 percent carbon (Penman et al. 2003) for all pools except forest floor, which is estimated as 37 percent carbon (Smith and Heath 2002). Carbon pools in the Stand Carbon Report are defined as follows (for additional details, consult Hoover and Rebain 2008 or the Fire and Fuels Extension documentation):

- Total Aboveground Live: carbon in live trees, including stems, branches, and foliage. Choice of calculation methods: either volume based default FVS-FFE methods (Rebain 2010, Reinhardt and Crookston 2003) or national biomass equations (Jenkins et al. 2003).
- Merchantable Aboveground Live: carbon in the merchantable portion of live trees; choice of calculation method as above.
- Belowground Live: carbon in coarse roots of live trees; carbon in fine roots is assumed to be part of the soil pool, not currently reported in FVS.
- Belowground Dead: carbon in coarse roots of dead or cut trees.

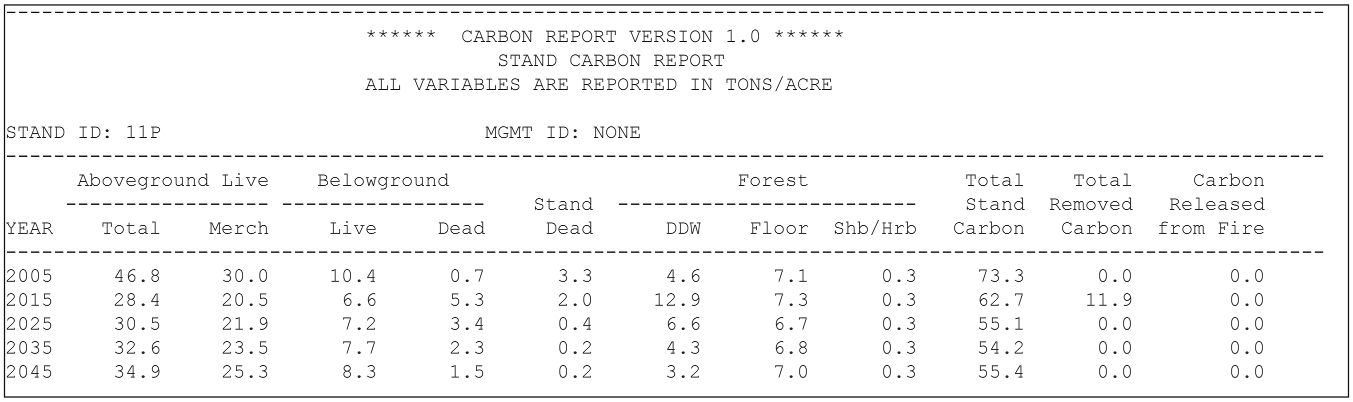
- Standing Dead: carbon in dead trees, including stems and any branches or foliage still present, but excluding roots.
- Down Dead Wood: all woody surface material regardless of size.
- Forest Floor: all surface organic material excluding wood (i.e., litter and duff); this definition is not an exact match with those used in 1605(b) reporting. Under the 1605(b) guidelines, fine woody debris (<3 inches) is included in the forest floor pool; in the FFE carbon reports, this material is included in the down dead wood pool. Future modifications include adding a category, fine woody debris, to the Stand Carbon Report and tracking this material separately.
- Herbs and Shrubs: carbon in live herbs and shrubs.

Other categories reported are Total Removed Carbon including carbon removed through cutting live or dead trees or hauling away surface fuel, and Carbon Released from Fire, which includes carbon in fuel consumed by simulated wildfires, prescribed burns, and pile-burns. This category is useful for comparing the carbon consequences of fuel management alternatives, because fire behavior, fuel consumption, and therefore carbon released, are based on the burn parameters entered. An example of the Stand Carbon Report, including a simulated thinning, is shown in Figure 1. Note that the Total Removed Carbon column is non-zero only in the year of harvest, 2015.

Because FVS is a stand dynamics model, the carbon pools change over time. For instance, the aboveground and belowground live and dead pools are initially based on the inventory data provided, but then change due to tree growth, mortality, and removals. In the case shown in Figure 1, the total aboveground live carbon is initially 46.8 tons/acre, then drops to 28.4 tons/acre after live trees are removed as part of the harvest, and then increases over the next 30 years to 34.9 tons/acre as the residual trees grow. Harvesting caused the live belowground carbon (live root carbon) to decrease from 10.4 to 6.6 tons/acre as some of this carbon is moved from the live belowground pool to the dead belowground pool. The dead belowground carbon decreases over time due to decay. The standing dead carbon then decreases over time from 3.3 to 0.2 tons/acre as these snags fall to the ground and become down dead wood.

Down dead wood and forest floor biomass are pools that users can initialize from inventory data. If site-specific data are not available, default values are provided for forest floor and various diameter classes of down dead wood. During a projection, these estimates fluctuate to take into account surface fuel decay as well as additions, such as litterfall, snagfall, and harvesting residues. As an example, in Figure 1, the down dead wood increases from 4.6 tons/acre to 12.9 tons/acre, because, in this example, crown material was left as slash during the harvest. The

Figure 1.—Screen shot of sample Stand Carbon Report, with a thin from below simulated in 2015.



```
--------------------------------------------------------------------------------------------------------------
                              ******  CARBON REPORT VERSION 1.0 ******
                                         STAND CARBON REPORT
                              ALL VARIABLES ARE REPORTED IN TONS/ACRE

STAND ID: 11P                           MGMT ID: NONE
--------------------------------------------------------------------------------------------------------------
      Aboveground Live    Belowground                        Forest             Total    Total     Carbon
     ----------------- -----------------    Stand  -------------------------    Stand  Removed   Released
YEAR    Total    Merch     Live     Dead     Dead      DDW    Floor  Shb/Hrb   Carbon   Carbon  from Fire
--------------------------------------------------------------------------------------------------------------
2005     46.8     30.0     10.4      0.7      3.3      4.6      7.1      0.3     73.3      0.0        0.0
2015     28.4     20.5      6.6      5.3      2.0     12.9      7.3      0.3     62.7     11.9        0.0
2025     30.5     21.9      7.2      3.4      0.4      6.6      6.7      0.3     55.1      0.0        0.0
2035     32.6     23.5      7.7      2.3      0.2      4.3      6.8      0.3     54.2      0.0        0.0
2045     34.9     25.3      8.3      1.5      0.2      3.2      7.0      0.3     55.4      0.0        0.0
```

herb and shrub estimates are initially based on stand attributes such as dominant species and density, and they change over time as stand conditions change. More details can be found in the FVS and FFE documentation (Dixon 2002, Rebain 2010, Reinhardt and Crookston 2003).

The Harvested Carbon Report tracks the fate of carbon in harvested merchantable material, including salvaged logs. Carbon in removed merchantable biomass is allocated into various pools and followed over time; for example, a product in use may be discarded, transferring carbon from the product pool into the landfill pool. Both merchantability specifications and allocation to harvested carbon pools differ by FVS variant. Choices made about units and methods of calculation for the Stand Carbon Report carry over to the Harvested Carbon Report. Carbon in harvested merchantable biomass is allocated following the methods of Smith et al. (2006) to the following pools:

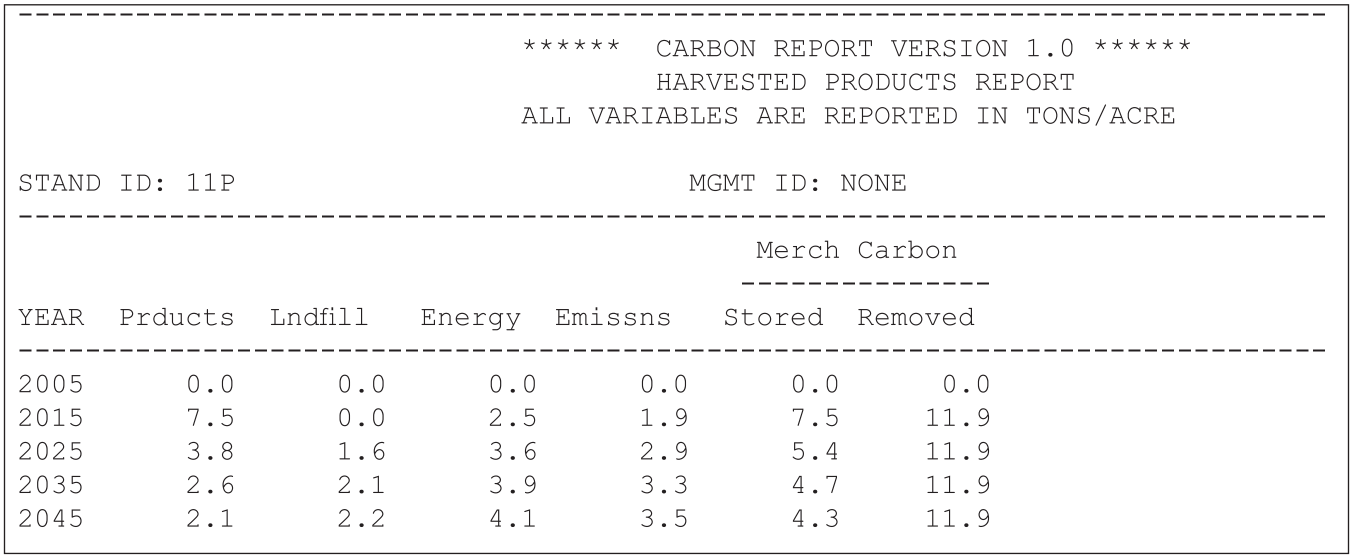
- Products in use
- Products in landfills
- Carbon emitted from combustion with energy capture
- Carbon emitted from combustion or decay without energy capture

Carbon in forest products and in landfills is summarized in the Merchantable Carbon Stored column of the Harvested Carbon Report, while the Merchantable Carbon Removed column reflects all of the carbon in merchantable biomass that was removed from the stand and is the sum of the four pools above. Over time, stored carbon from a particular harvest will shift to one of the other categories.

An example of the Harvested Carbon Report is given in Figure 2. In this example, 11.9 tons/acre of carbon was removed from the stand during the harvest, but initially only 7.5 tons/acre of that was stored in forest products. Over time, carbon stored in forest products in use declines, as some moves to landfills and some decays or is burned. At the end of the simulation, 4.3 tons/acre of the initial removal was still storing carbon.

While carbon removed from the stand is reported in the year of harvest in the Stand Carbon Report, the carbon contained in earlier removals is not included, nor is the carbon accounted for once it leaves the stand. Consequently, if harvesting is simulated, you should request both reports and add the number in the Merchantable Carbon Stored column from the Harvested Carbon Report to the corresponding value

Figure 2.—Screen shot of sample Harvested Carbon Report, with a thin from below simulated in 2015.



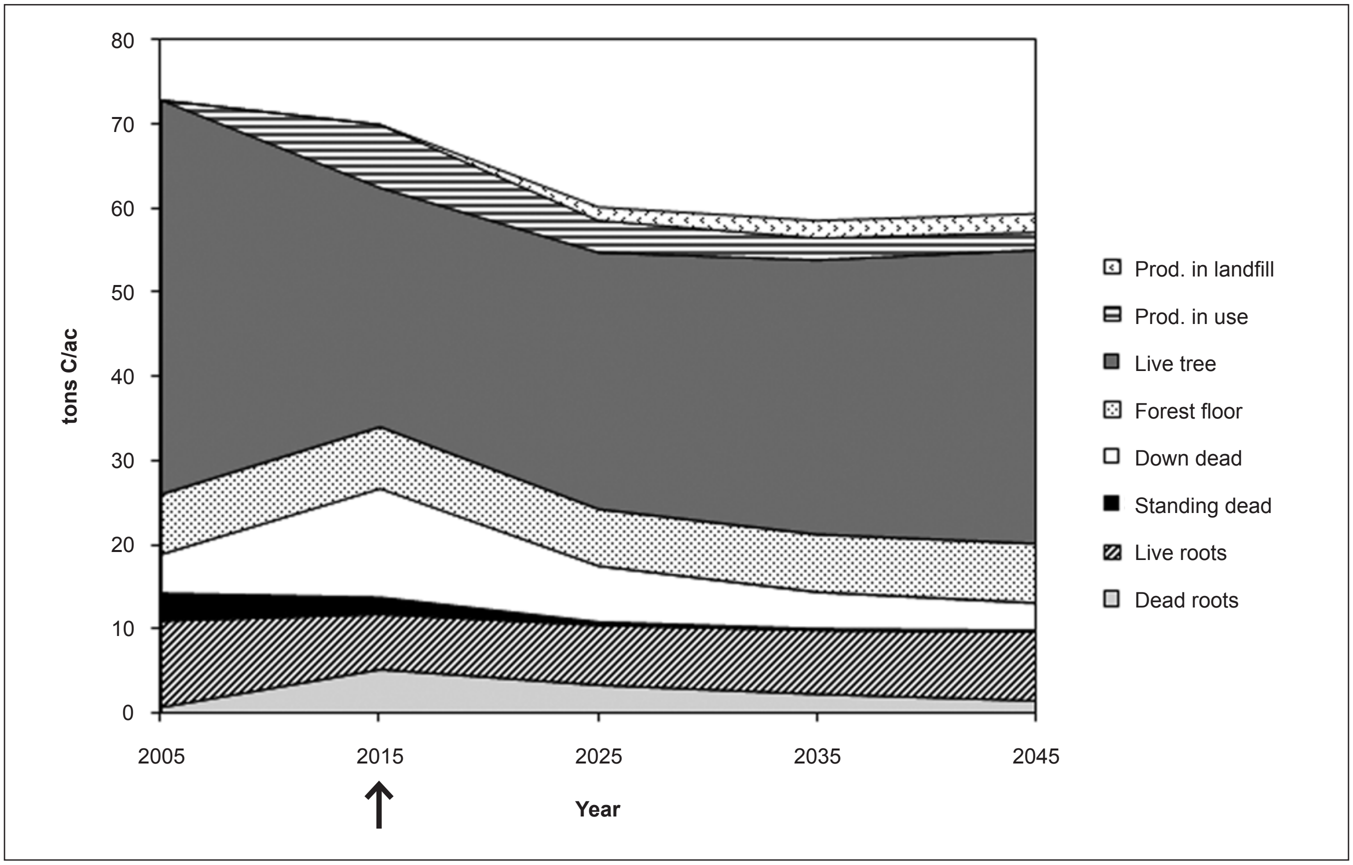
```
------------------------------------------------------------------------------
                              ******  CARBON REPORT VERSION 1.0 ******
                                      HARVESTED PRODUCTS REPORT
                              ALL VARIABLES ARE REPORTED IN TONS/ACRE

STAND ID: 11P                           MGMT ID: NONE
------------------------------------------------------------------------------
                                            Merch Carbon
                                           ---------------
YEAR  Prducts  Lndfill  Energy  Emissns   Stored  Removed
------------------------------------------------------------------------------
2005      0.0      0.0      0.0      0.0      0.0      0.0
2015      7.5      0.0      2.5      1.9      7.5     11.9
2025      3.8      1.6      3.6      2.9      5.4     11.9
2035      2.6      2.1      3.9      3.3      4.7     11.9
2045      2.1      2.2      4.1      3.5      4.3     11.9
```

in the Total Stand Carbon column from the Stand Carbon Report to estimate total carbon sequestered. As an example, to obtain the total amount of carbon sequestered in 2015, add the total stand carbon from the Stand Carbon Report (Figure 1, 62.7 tons C/ac) and the merchantable stored carbon from the Harvested Carbon Report (Figure 2, 7.5 tons C/ac) for a total of 70.2 tons C/ac of sequestered carbon in 2015. This calculation should be repeated for each reporting year. Both the Stand Carbon and Harvested Carbon reports may be sent to an external database or spreadsheet using the database extension of FVS (Crookston et al. 2003), allowing quick calculation of total carbon estimates for scenarios where harvests have occurred. Figure 3 shows the carbon pools over time for the stand shown in Figures 1 and 2.

One of the challenges in accounting for carbon in harvested wood products is the role of imports and exports—does the location that produced the timber receive credit, or is credit assigned to the importing location? The Harvested Carbon Report uses the production approach to trade; that is, the fate of the carbon in the harvested wood products is calculated for all harvested wood produced, regardless of whether the wood will be used locally or exported. If the wood is exported after harvest, the carbon it contains is treated the same as other wood harvested from the site; it is not transferred or credited to another location. This reduces the chances of double counting carbon in the harvested wood products pool. The methods and coefficients applied in the Harvested Carbon Report are described in detail in Smith et al. (2006).

Figure 3.—Projected carbon changes over time for the stand in Figure 1. Shrub and herb carbon has been omitted. The arrow indicates the year of thinning.



Increasingly, forest managers are being asked to consider the potential carbon consequences of forest management actions. The possibility of earning income from the sale of carbon credits further highlights the need for projections of forest carbon stocks into the future. While there are multiple carbon registries at this time, many require that forest carbon storage be “additional”—that is, above and beyond business as usual—to receive credit as an emission offset. Determining this baseline level of carbon storage can be difficult, but this is another area where the carbon reporting functions can help managers. Using data from an appropriately designed forest inventory, managers can generate baseline carbon stock estimates by simulating the “business as usual” management actions for any given tract. Alternative management scenarios can then be simulated, and the carbon stock estimates and average annual change can be compared for a variety of management alternatives in the same manner that FVS is generally used to compare the outcomes of various management options. For example, if “business as usual” is to rely on natural regeneration after a disturbance, you could simulate this in FVS and estimate carbon storage. To estimate carbon storage under a second scenario, one where desirable tree species are planted instead, a second simulation could be run with the planting specifications. By comparing the two simulations, you can determine how much (if any) additional carbon may be stored by planting trees instead of relying on natural regeneration.

GENERATING THE REPORTS – CARBON KEYWORDS

The keywords needed to generate carbon reports can be found in the FFE menu in Suppose, the graphical user interface for FVS. Three main keywords relate to the carbon accounting functions. CarbRept requests the Stand Carbon Report and CarbCut requests the Harvested Carbon Report. The CarbCalc keyword is used to select the biomass prediction method, reporting units, and annual decay rate of coarse roots. To assist with output analysis, both reports can be sent to an external database or spreadsheet using the CarbRpts keyword in the database extension menu in Suppose. A secondary option for FVS users who are not as familiar with individual keywords is to request, adjust, and export the carbon reports by choosing “Select Outputs” and then “FFE Carbon Reports.”

Example: Bartlett Experimental Forest

The Bartlett Experimental Forest (BEF) is a northern hardwood forest of about 5,790 acres in the White Mountains of central New Hampshire. The BEF, originally 2,600 acres, was expanded to its present area in 2005 to meet ongoing research needs. The most recent inventory was conducted from 2001 to 2003, before the expansion. All live stems 2 inches d.b.h. and over were tallied on 440 permanent cruise plots, which are generally 0.25 acres in size. This information on inventory design is used by FVS to produce the correct per acre expansion factors. The inventory data from these plots were run through the FVS system; the resulting current carbon stocks for BEF are given in Table 1. Because the carbon stock estimates are produced by applying conversion factors to the standard biomass estimates generated by FVS and the FFE, the accuracy of the carbon reports depends on the accuracy and adequacy of the inventory data supplied by the user. Users need to make certain that their forest inventory design is appropriate and that a sufficient number of plots have been measured to ensure meeting the error level specified in the inventory design. Supplying as much information as possible will also improve the projections and estimates; while tree height is not a required input variable, adding it will improve model performance. Similarly, if data on down dead wood and forest floor mass are available, including these instead of relying on regional default values is advised.

As a simple illustration, the data from BEF were used to run projections of carbon stocks over the next 40 years, with no management actions simulated. The current version of the northeast variant was used and local values were input for site index, slope, aspect, and elevation. Mortality and growth rates were left at their default settings, and seedlings were added periodically to simulate natural background regeneration (only a few of the geographic variants include automatic regeneration; aside from stump sprouts, users must specify the size and amount of seedlings by species). Table 2 shows the carbon stocks from this base projection, including average annual change in carbon stocks for each 10-year period and for the entire projection. If harvesting is simulated, the Stand Carbon Report will include the carbon in logging slash (by default, crowns are added to the down dead wood and forest floor pools), while the Harvested Carbon Report includes merchantable carbon in wood products and landfills (see Figures 1 and 2 for examples of these reports). Again, users must add the value in the Merchantable Carbon Stored column from the Harvested Carbon Report to the value in the Total Stand Carbon column in the Stand Carbon Report to account for all pools when a harvest occurs. This must be done for each reporting year following a harvest.

Table 1.—Carbon stocks on the Bartlett Experimental Forest in 2005

Pool	Tons C/acre	Tons C forest-wide
Aboveground live biomass	44.1	255,339
Belowground live biomass	10.2	59,058
Standing dead	2.9	16,791
Belowground dead biomass	0.7	4,053
Down dead wood	4.5	26,055
Forest floor	7.3	42,267
Shrubs and herbs	0.3	1,737
Total	70.0	405,300

Table 2.—Projected carbon stocks on the Bartlett Experimental Forest, 2005-2045

Year	Base Growth Scenario (tons C/acre)	Average Annual Change (tons C/acre/yr) [a]
2005	70.0	
2015	74.5	0.45
2025	78.8	0.43
2035	82.6	0.38
2045	86.1	0.35
2005-2045		0.40

[a] Average annual change is for each 10-year period, e.g., 2005-2015, 2015-2025

COMMON QUESTIONS: SEVEN THINGS YOU NEED TO KNOW

Should carbon stocks be analyzed, or change calculated over time?

The Stand Carbon Report provides an estimate of the amount, or stock, of carbon at a specified point in time. While carbon stock estimates are important, when comparing management alternatives it is most useful to compute the rate of change over time (average annual change). The average annual change in carbon stocks is similar to periodic annual increment and is simply calculated by taking the difference between the carbon stock at Time 2 and Time 1 and dividing by the number of years between the two. This gives the rate of change for that time period; note that short-term and long-term rates may differ for any given management alternative. When framing an analysis, the management objectives should be considered and the time frame should be chosen to reflect those objectives. For the BEF case study above (Table 2), the rate of average annual change in carbon from 2005 to 2015 is:

(74.5 tons C/ac – 70 tons C/ac) / 10 years =
0.45 tons C/ac/year

This calculation can easily be made for any pool; e.g., live aboveground biomass only or all live biomass in trees. Users may be tempted to run FVS with a cycle length of 1 year to generate annual estimates, but this practice is discouraged because the default cycle lengths are related to the increment data on which the growth models were built. Using cycle lengths other than the default (10 years in most variants) may result in underprediction or overprediction of stand attribute values relative to those obtained using the default (Wykoff et al. 1982). A few 1-year cycles within a simulation will not significantly bias simulation results, but creation of whole simulations with 1-year cycles is discouraged. To produce annual estimates, it is good practice to compute average annual change as described above. In general, annual changes in carbon stocks are difficult to field verify because the carbon increment for a single year will often be within the bounds of measurement error, while changes in carbon pools over a longer period are generally within detection limits.

FVS is a stochastic model; however, by default, the same random number seed is used and so the same simulation file produces the same results with each run. Random effects are incorporated in the model through the distribution of errors associated with the prediction of the logarithm of basal area increment. The effects of these differing diameter growth rates extend through most of the remaining components of the model (Dixon 2002). It is possible to reset the random number seed to produce variation in projection results with the RANNSEED keyword. Hamilton (1991) suggests several projections should be made using different random seeds rather than relying on the results of a single simulation. When estimating carbon, it is good practice to follow this recommendation of multiple model runs in a stochastic manner to get some knowledge of the expected variation around the estimate.

Does regeneration occur automatically in simulations?

Probably not. Some FVS variants, such as Inland Empire, Eastern Montana, Central Idaho, and Southeast Alaska, have a full establishment model that predicts incoming regeneration over time. The rest of the variants do not—in these cases the only regeneration occurring automatically is from sprouting following a harvest or fire. As a result, depending on the length of your simulations and the types of management practices simulated, you may need to decide on regeneration rates and input them through keywords. Regeneration amounts may be derived from expert opinion or literature sources, or they may be inferred through other inventory data sources. **Regeneration rates should be carefully considered since they may have a substantial impact on your simulation results.**

Does FVS estimate soil carbon?

The soil carbon pool is currently not included in the carbon reports. Soil carbon stocks are highly variable across the landscape and do not respond to management actions in a uniform manner. While some estimates of soil carbon are available, they are quite general and for that reason are not included at this time. The status of forest soil carbon data and models is being monitored, and soil carbon may be included in the reports in the future.

What about cases where only live trees or large trees were inventoried? Will some carbon pools be missing from the reports?

The trees initially included in FVS simulations are those in your input dataset. To ensure all carbon pools are modeled, you must inventory small and dead trees, as well as large, live trees. If estimates of surface fuels (down dead wood) are available, they should be input to the model as well. If no surface fuel data are available, FVS dubs in initial values based on the forest type and other stand characteristics, depending on the variant you are running.

Does FVS work for all forest types?

FVS variants cover most forested areas of the United States. However, these variants were developed to generally describe forest growth in that region—each variant can and should be calibrated to local site conditions. Once a variant is selected, there are multiple ways to calibrate FVS to better match the site conditions (Hamilton 1994, Ray et al. 2009, Vandendriesche and Haugen 2008). One simple thing is to make sure important variables that drive the growth and mortality equations are included in your input dataset. These vary by variant but typically include topographic variables (slope, aspect, and elevation) and site productivity variables (such as site index or habitat type). Reading the variant overview documentation for the specific area you are modeling is essential to know what to include. FVS also has a self-calibration feature that allows growth measurements to be entered and then used to adjust the default growth equations so that they better match a stand's particular site conditions.

Which method of biomass calculation is the best choice?

This depends on the scale of your analysis as well as on site factors. The default setting uses the regional volume equations from the National Volume Estimator Library, the standard method used by FVS. These volume estimates are then converted to biomass using species-specific pounds/cubic foot conversion factors. Because the volume equations do not include crown material, separate crown biomass equations are used to calculate the additional carbon in this portion of the tree. If you are working with just one geographic variant, this method is likely a good choice, since the equations are more local. If you are conducting analyses using several different geographic variants and comparing them, then you may wish to select the Jenkins et al. (2003) calculation option, which uses national biomass equations. This will eliminate possible differences in carbon estimates due to differences in the behavior of the regional volume equations. If the Jenkins et al. (2003) calculation option is chosen, it is used to calculate the live tree carbon in both the Stand Carbon Report and Harvested Carbon Report.

Does FVS estimate carbon or carbon dioxide equivalents?

The output units in the carbon reports are chosen by the user; while there are three choices, tons/acre, metric tons/hectare, or the hybrid unit of metric tons/acre, **all** output is in mass of carbon regardless of the unit selected. Those users who require output in terms of carbon dioxide will need to convert to carbon dioxide equivalent (CO_2e), which is easily done by multiplying the mass of carbon by 44/12, the molecular weight ratio of carbon dioxide to carbon. For nearly all reporting applications requiring the use of CO_2e, the units are metric tons rather than English tons.

LIMITATIONS OF THE REPORTS

The carbon reporting function was added to FVS primarily as a decision support tool for forest managers who need to address the carbon consequences of planned management actions and their alternatives. While this tool may be used to develop carbon sequestration estimates for carbon credit trading, the reports were not originally designed for this purpose and may not include some carbon pools that may be of interest to those engaged in reporting overall carbon emissions and sequestration. These include management related emissions such as the carbon emitted from equipment use when harvesting and transporting timber, transporting nursery stock for planting, etc. A complete carbon footprint analysis would include life-cycle analysis of all aspects of forest management, such as the emissions associated with the production, transportation, and application of fertilizer. FVS was designed as a growth and yield model; the carbon reporting functions simply convert standard FVS outputs to biomass and then to carbon using the assumptions detailed above and referenced in the model documentation. Full entity-wide carbon accounting is beyond the scope of FVS.

SUMMARY

By building on the existing capabilities of the FFE, we integrated easy-to-use, comprehensive carbon accounting capabilities into FVS. Managers familiar with the model can now estimate carbon stocks and assess the carbon implications of different management practices along with more traditional management objectives by using just a few additional keywords. **It is important to note that the usual recommendations and guidance for running simulations in FVS apply; the carbon reports simply build on standard FVS outputs.** Those wishing to use the carbon reporting functions in FVS should be aware of the inventory and stand data requirements for their particular FVS variant, and calibrate the model to local conditions as much as possible. When using FVS for any purpose, including estimating carbon stocks, it is critical to begin with data from an appropriately designed forest inventory that meets a suitable level of error (generally ± 10 or 20 percent). FVS is constantly being improved and updated. As a result, the estimates of carbon may change based on the version of the software you are using. A list of bulletins describing updates and improvements to the various FVS components is maintained on the FVS Web site.

FVS is an extensive and complex model that can simulate nearly any forest management treatment. With this flexibility and complexity comes a fairly steep learning curve; **it is strongly recommended that users have prior FVS experience or attend FVS training before attempting to use the model.** Training sessions are held throughout the year; information on FVS training sessions can be found on the FVS Web site.

ACKNOWLEDGMENTS

The authors would like to thank Linda Heath, Chad Keyser, and Mariko Yamasaki for feedback on an early draft of the manuscript. The final manuscript benefited from reviews and suggestions from Elizabeth Reinhardt, Robert Smith, Erin Smith-Mateja, and Michael VanDyck. We are grateful to Eric Fiegenbaum for creating the cover art and to Michael VanDyck for providing the map in Appendix B.

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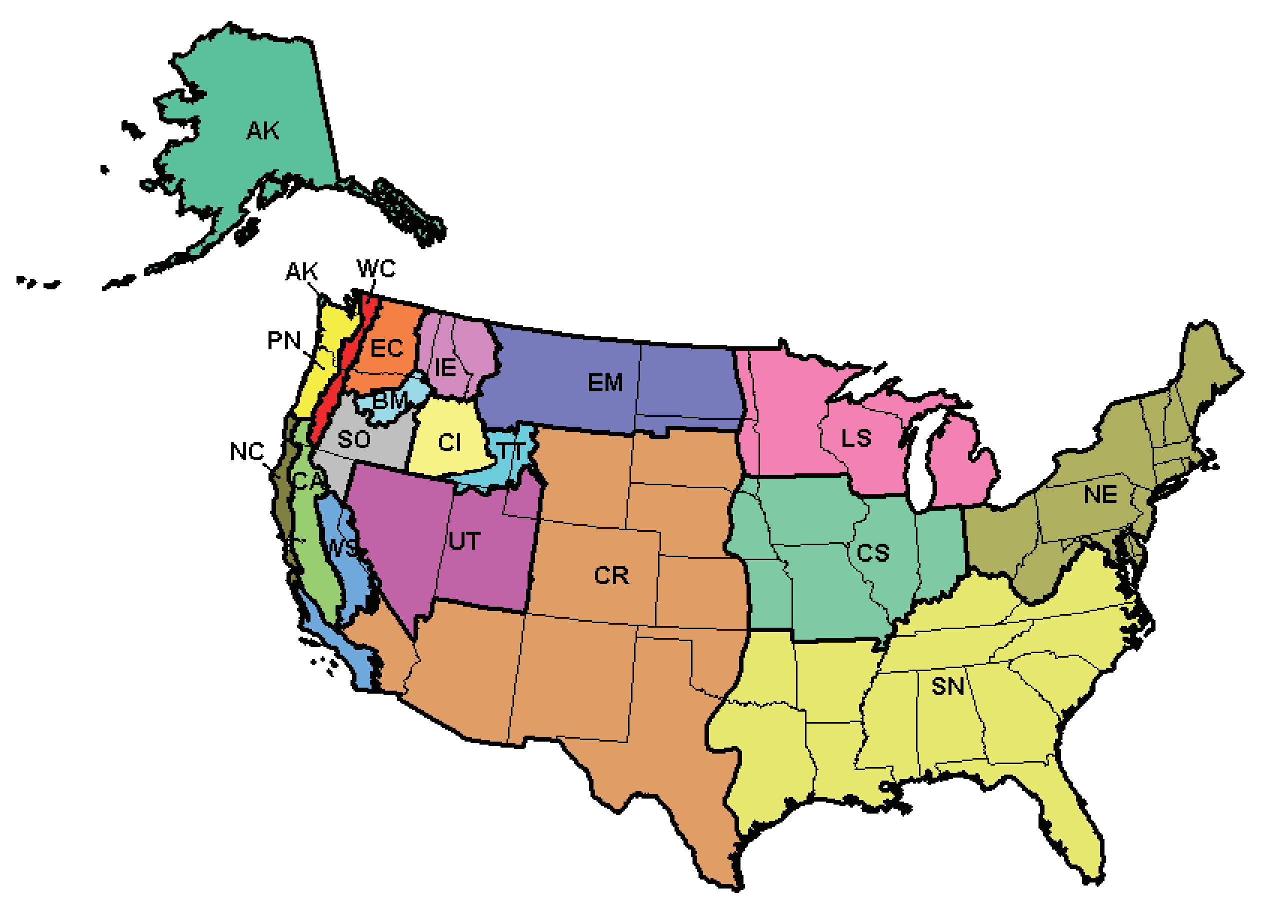
APPENDIX A – FVS OUTPUT TABLES

Table A-1—List of some available FVS output; this is not an exhaustive list.

Report or Post Processor	Variables Included
Summary Statistics Report	Trees per acre, basal area, stand density index, quadratic mean diameter, stand top height, volume, and others
Output Tree List	Detailed individual tree output
Stand and Stock Table post processor	Trees per acre, basal area, and volume by species and diameter class
SVS post processor	Stand Visualization System image files
Compute variables	Virtually anything can be computed; includes trees per acre, basal area, volume, canopy cover, and other attributes by species and size class for live or harvested trees, fuel loading by size class, snags, tree biomass by species and size class, and many others
Potential Fire Report	Canopy base height, canopy bulk density, crowning index, torching index, potential fire type, flame length, mortality, smoke production, and fuel models
Fuels Report	Surface fuel and standing tree biomass in tons/acre
Summary Snag Report	Snags per acre by size and decay class (hard/soft)
Detailed Snag Report	Detailed snag output by species, size, decay class, and year of death
Fuel Consumption Report	Fuel consumption and smoke production for simulated burns
Burn Conditions Report	Fire behavior for simulated burns
Mortality Report	Mortality by size and species for simulated burns
Structure Class Report	Canopy cover, stand structure class, and others

APPENDIX B – FVS VARIANTS



Southeast Alaska and Coastal British Columbia (AK)
Blue Mountains (BM)
Inland California and Southern Cascades (CA)
Central Idaho (CI)
Central Rockies (CR)
Central States (CS)
East Cascades (EC)
Eastern Montana (EM)
Klamath Mountains (NC)
Lake States (LS)
Northeast (NE)
Inland Empire (IE)
Pacific Northwest Coast (PN)
Southern (SN)
South Central Oregon and Northeast California (SO)
Tetons (TT)
Utah (UT)
Westside Cascades (WC)
Western Sierra Nevada (WS)

APPENDIX C – STAND AND TREE INPUT VARIABLES

Table C-1.—List of tree variables that can be input into FVS. Items in bold type are required.

Variable	**Description**
Tree_ID	Tree Identification Code
Plot_ID	Plot Identification
Tree_Count	Tree Count
History	History Code 0-5 are live trees, 6 and 7 died during mortality observation, 8 and 9 died before mortality observation period
Species	**Tree Species Code, can be the FVS alpha code, FIA code, or USDA plant symbol**
DBH or Diameter	**Diameter at breast height (dbh) in inches**
DG	DBH growth in inches
Ht	Height in feet
HtG	Height growth in feet
HtTopK	Height to the point of the tree of top kill in feet
CrRatio	If the number is 0-9, then it is considered a crown ratio code. If the number is 10-99, the value is considered a percent live crown.
Damage1 - 3	Three damage codes can be input
Severity1 - 3	The associated severity code for each damage code
TreeValue	Tree Value Class Code 1 for desirable, 2 for acceptable, 8 for non-stockable, and any other number represents a live cull
Prescription	Prescription code
Age	Age of the tree record

Table C-2.—List of stand variables that can be input into FVS. Items in bold type are required.

Variable	**Description**
Stand_ID	**Stand identification code**
Stand_CN	Stand control number; a unique stand identifier
Variant	**The two-character variant identification code**
Inv_Year	**The stand’s inventory year**
Latitude	Latitude in degrees of the stand’s location
Longitude	Longitude in degrees of the stand’s location
Location	Location code representing the Region/Forest/District/Compartment codes
Ecoregion	Bailey’s Ecoregion code
PV_Code or Habitat	The habitat type or plant association code
PV_Ref_Code	Potential vegetation reference code for the PV_Code
Age	Stand age in years
Aspect	Aspect in degrees
Slope	Slope in percent
ElevFt	Elevation in feet

(Table C-2 continued on next page)

APPENDIX C – STAND AND TREE INPUT VARIABLES (continued)

Table C-2. (continued)—List of stand variables that can be input into FVS. Items in bold type are required.

Variable	**Description**
Basal_Area_Factor	**Basal area factor used in sampling large trees**
Inv_Plot_Size	**The inverse of the fixed plot size in acres used in sampling small trees**
Brk_DBH	**Breakpoint DBH in inches between small tree and large tree plots**
Num_Plots	Number of plots
NonStk_Plots	Number of non-stockable plots
Sam_Wt	Sampling weight used to compute weighted averages
Stk_Pcnt	Stockable percent
DG_Trans	Diameter growth translation code
DG_Measure	Diameter growth measurement period
HTG_Trans	Height growth translation code
HTG_Measure	Height growth measurement period
Mort_Measure	Mortality measurement period
Max_BA	Maximum basal area
Max_SDI	Maximum stand density index
Site_Species	Site species code
Site_Index	Site index
Model_Type	Model type code
Forest_Type	Forest type code
State	FIA state code
County	FIA county code
Fuel_Model	Fire behavior fuel model
Fuel_0_25	Initial tons per acre of 0 to 0.25 inch fuel
Fuel_25_1	Initial tons per acre of 0.25 to 1 inch fuel
Fuel_1_3	Initial tons per acre of 1 to 3 inch fuel
Fuel_3_6	Initial tons per acre of 3 to 6 inch fuel
Fuel_6_12	Initial tons per acre of 6 to 12 inch fuel
Fuel_12_20	Initial tons per acre of 12 to 20 inch fuel
Fuel_20_35	Initial tons per acre of 20 to 35 inch fuel
Fuel_35_50	Initial tons per acre of 35 to 50 inch fuel
Fuel_gt_50	Initial tons per acre of greater than 50 inch fuel
Fuel_Litter	Initial tons per acre of litter
Fuel_Duff	Initial tons per acre of duff
Photo_Ref	Photo series reference number (1 – 32)
Photo_Code	Photo reference number

Hoover, Coeli M.; Stephanie A. Rebain. 2011. **Forest Carbon Estimation Using the Forest Vegetation Simulator: Seven Things You Need to Know.** Gen. Tech. Rep. NRS-77. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 16 p.

Interest in options for forest-related greenhouse gas mitigation is growing, and so is the need to assess the carbon implications of forest management actions. Generating estimates of key carbon pools can be time consuming and cumbersome, and exploring the carbon consequences of management alternatives is often a complicated task. In response to this, carbon reporting capability has been added to the Forest Vegetation Simulator (FVS) growth and yield modeling system, allowing users to produce carbon reports along with traditional FVS outputs. All methods and computations are consistent with Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance and U.S. voluntary carbon accounting rules and guidelines. We briefly describe the FVS system, outline the carbon pools estimated, and provide an overview of the data requirements, capabilities, features, and limitations of the model and the carbon reports. We also review common questions and pitfalls encountered by users when running the model.

KEY WORDS: Forest Vegetation Simulator, forest carbon estimation, forest carbon sequestration, harvested wood products

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Appendix II

Central States Variant Overview

USDA (2016)

United States
Department of
Agriculture

Forest Service

Forest Management
Service Center

Fort Collins, CO

2008

Revised:

April 2016

Central States (CS) Variant Overview

Forest Vegetation Simulator

Hoosier NF
(Bob Stone, FS-R9)

Central States (CS) Variant Overview

Forest Vegetation Simulator

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The FVS staff has maintained model documentation for this variant in the form of a variant overview since its release in 1993. The original author was Renate Bush. In 2006, Gary Dixon reformulated many of the model components, created a test version of the variant and wrote this new variant overview. In 2008, the previous document was replaced with this updated variant overview. Gary Dixon, Christopher Dixon, Robert Havis, Chad Keyser, Stephanie Rebain, Erin Smith-Mateja, and Don Vandendriesche were involved with this update. Gary Dixon cross-checked information contained in this variant overview with the FVS source code. Current maintenance is provided by Chad Keyser.

Dixon, Gary E.; Keyser, Chad E., comps. 2008 (revised April 4, 2016). Central States (CS) Variant Overview – Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 51p.

Table of Contents

Quick Guide to Default Settings

Parameter or Attribute	**Default Setting**	
Number of Projection Cycles	1 (10 if using Suppose)	
Projection Cycle Length	10 years	
Location Code (National Forest)	905 – Mark Twain	
Slope	5 percent	
Aspect	0 (no meaningful aspect)	
Elevation (default location)	10 (1000 feet)	
Latitude (default location)	37.95	
Longitude (default location)	91.77	
Site Species	WO	
Site Index	65 feet (total age; 50 years)	
Maximum Stand Density Index	Species specific	
Maximum Basal Area	Species specific	
Volume Equations	National Volume Estimator Library	
Pulpwood Volume Specifications:		
Minimum DBH / Top Diameter	Hardwoods	Softwoods
905 – Mark Twain	5.0 / 4.0 inches	5.0 / 4.0 inches
908 – Shawnee	6.0 / 5.0 inches	5.0 / 4.0 inches
911 – Wayne-Hoosier, 912 - Hoosier	6.0 / 4.0 inches	5.0 / 4.0 inches
Stump Height	0.5 feet	0.5 feet
Merchantable Sawlog Volume Specifications:		
Minimum DBH / Top Diameter	Hardwoods	Softwoods
905 – Mark Twain (eastern redcedar)		6.0 / 5.0 inches
905 – Mark Twain (all other species)	9.0 / 7.6 inches	9.0 / 7.6 inches
908 – Shawnee	11.0 / 9.6 inches	9.0 / 7.6 inches
911 – Wayne-Hoosier, 912 - Hoosier	11.0 / 9.6 inches	9.0 / 7.6 inches
Stump Height	1.0 foot	1.0 foot
Sampling Design:		
Basal Area Factor	40 BAF	
Small-Tree Fixed Area Plot	1/300th Acre	
Breakpoint DBH	5.0 inches	

1.0 Introduction

The Forest Vegetation Simulator (FVS) is an individual tree, distance independent growth and yield model with linkable modules called extensions, which simulate various insect and pathogen impacts, fire effects, fuel loading, snag dynamics, and development of understory tree vegetation. FVS can simulate a wide variety of forest types, stand structures, and pure or mixed species stands.

New “variants” of the FVS model are created by imbedding new tree growth, mortality, and volume equations for a particular geographic area into the FVS framework. Geographic variants of FVS have been developed for most of the forested lands in the United States.

The original Central States (CS) variant was developed in 1993 using relationships from the CS-TWIGS model (Shifley 1987; Miner and others 1988), and equations from other variants for FVS relationships not present in CS-TWIGS. The model was reformulated in 2006 to improve model estimates; the only remnant of the original CS-TWIGS formulation is in the large tree diameter growth equation.

To fully understand how to use this variant, users should also consult the following publication:

- Essential FVS: A User’s Guide to the Forest Vegetation Simulator (Dixon 2002)

This publication can be downloaded from the Forest Management Service Center (FMSC), Forest Service website or obtained in hard copy by contacting any FMSC FVS staff member. Other FVS publications may be needed if one is using an extension that simulates the effects of fire, insects, or diseases.

2.0 Geographic Range

The CS variant covers forested areas in Illinois, Indiana, Iowa, and Missouri. This includes the Shawnee National Forest in Illinois, the Hoosier National Forest in Indiana, and the Mark Twain National Forest in Missouri. The suggested geographic range of use for the CS variant is shown in figure 2.0.1.

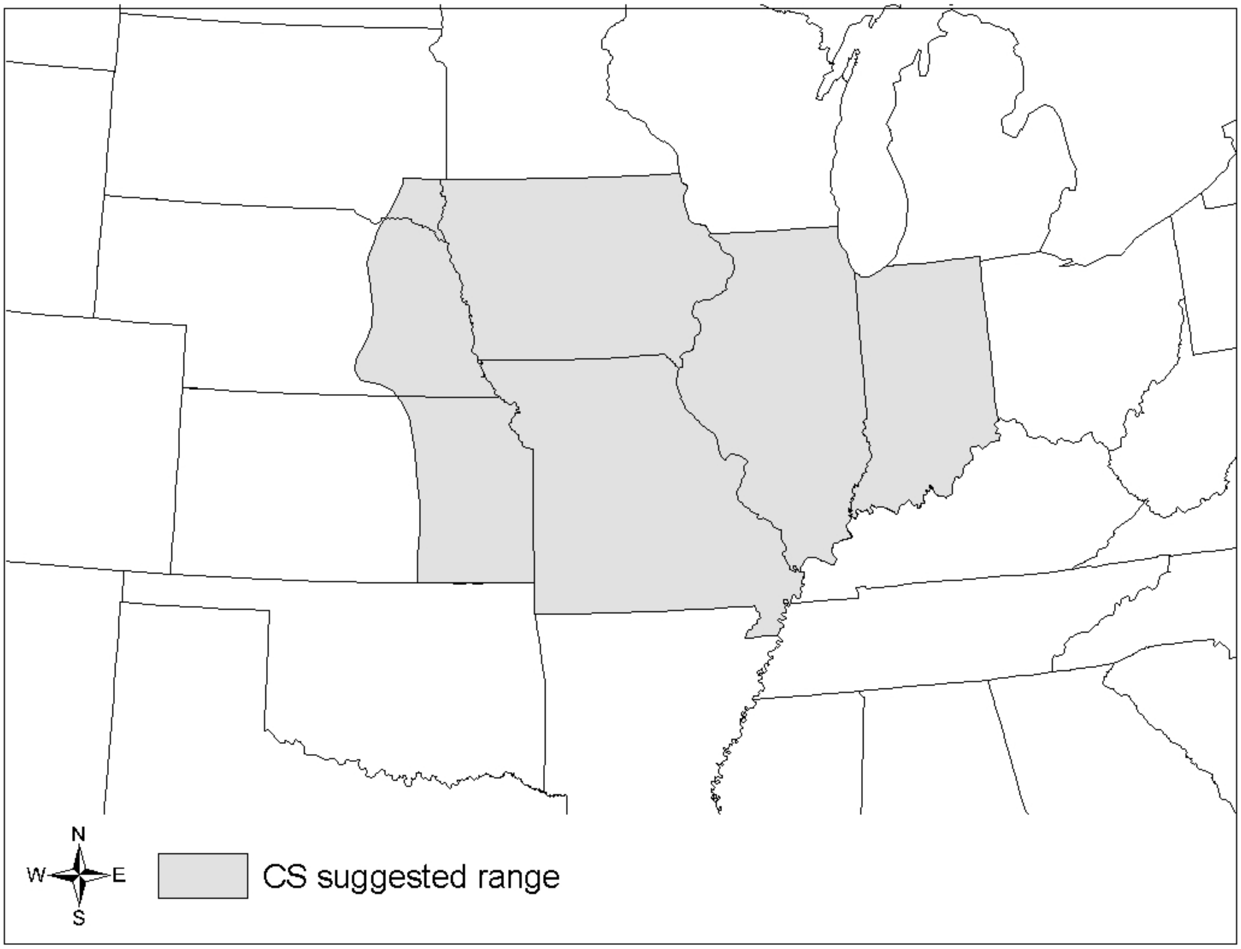

Figure 2.0.1 Suggested geographic range of use for the CS variant.

3.0 Control Variables

FVS users need to specify certain variables used by the CS variant to control a simulation. These are entered in parameter fields on various FVS keywords usually brought into the simulation through the SUPPOSE interface data files or they are read from an auxiliary database using the Database Extension.

3.1 Location Codes

The location code is a 3-digit code where, in general, the first digit of the code represents the Forest Service Region Number, and the last two digits represent the Forest Number within that region.

If the location code is missing or incorrect in the CS variant, a default forest code of 905 (Mark Twain National Forest) will be used. A complete list of location codes recognized in the CS variant – and their associated default latitude, longitude, and elevation values – are shown in table 3.1.1.

Table 3.1.1 Location codes used in the CS variant.

Location Code	USFS National Forest	Latitude	Longitude	Elevation
905	Mark Twain	37.95	91.77	10 (1000 feet)
908	Shawnee	37.74	88.54	4 (400 feet)
912	Hoosier	38.86	86.49	6 (600 feet)
911	Wayne-Hoosier combined code (mapped to 912)	38.86	86.49	6 (600 feet)

3.2 Species Codes

The CS variant recognizes 96 species. You may use FVS species codes, Forest Inventory and Analysis (FIA) species codes, or USDA Natural Resources Conservation Service PLANTS symbols to represent these species in FVS input data. Any valid eastern species codes identifying species not recognized by the variant will be mapped to the most similar species in the variant. The species mapping crosswalk is available on the variant documentation webpage of the FVS website. Any non-valid species code will default to the "non-commercial hardwoods" category.

Either the FVS sequence number or alpha code must be used to specify a species in FVS keywords and Event Monitor functions. FIA codes or PLANTS symbols are only recognized during data input, and may not be used in FVS keywords. Table 3.2.1 shows the complete list of species codes recognized by the CS variant.

Table 3.2.1 Species codes used in the CS variant.

Species Group	Species Number	Species Code	Common Name	FIA Code	PLANTS Symbol	Scientific Name
1	1	RC	eastern redcedar	068	JUVI	*Juniperus virginiana*
1	2	JU	juniper species	057	JUNIP	*Juniperus spp.*
2	3	SP	shortleaf pine	110	PIEC2	*Pinus echinata*
3	4	VP	Virginia pine	132	PIVI2	*Pinus viginiana*
3	5	LP	loblolly pine	131	PITA	*Pinus taeda*

Species Group	Species Number	Species Code	Common Name	FIA Code	PLANTS Symbol	Scientific Name
4	6	OS	other softwood species	298	2TE	
4	7	WP	eastern white pine	129	PIST	*Pinus strobus*
5	8	WN	black walnut	602	JUNI	*Juglans nigra*
5	9	BN	butternut	601	JUCI	*Juglans cinerea*
6	10	TL	tupelo species	690	NYSSA	*Nyssa spp.*
6	11	TS	swamp tupelo	694	NYBI	*Nyssa biflora*
6	12	WT	water tupelo	691	NYAQ2	*Nyssa aquatica*
6	13	BG	blackgum, black tupelo	693	NYSY	*Nyssa sylvatica*
7	14	HS	select hickory			
7	15	SH	shagbark hickory	407	CAOV2	*Carya ovata*
7	16	SL	shellbark hickory	405	CALA21	*Carya laciniosa*
7	17	MH	mockernut hickory	409	CAAL27	*Carya tomentosa*
8	18	PH	pignut hickory	403	CAGL8	*Carya glabra*
8	19	HI	hickory species	400	CARYA	*Carya spp.*
8	20	WH	water hickory	401	CAAQ2	*Carya aquatica*
8	21	BH	bitternut hickory	402	CACO15	*Carya cordiformis*
8	22	PE	pecan	404	CAIL2	*Carya illinoinensis*
8	23	BI	black hickory	408	CATE9	*Carya texana*
9	24	AB	American beech	531	FAGR	*Fagus grandifolia*
10	25	BA	black ash	543	FRNI	*Fraxinus nigra*
10	26	PA	pumpkin ash	545	FRPR	*Fraxinus profunda*
10	27	UA	blue ash	546	FRQU	*Fraxinus quadrangulata*
11	28	EC	eastern cottonwood	742	PODE3	*Populus deltoides*
12	29	RM	red maple	316	ACRU	*Acer rubrum*
12	30	BE	boxelder	313	ACNE2	*Acer negundo*
12	31	SV	silver maple	317	ACSA2	*Acer saccharinum*
13	32	BC	black cherry	762	PRSE2	*Prunus serotina*
14	33	AE	American elm	972	ULAM	*Ulmus americana*
14	34	SG	sugarberry	461	CELA	*Celtis laevigata*
14	35	HK	hackberry	462	CEOC	*Celtis occidentalis*
14	36	WE	winged elm	971	ULAL	*Ulmus alata*
14	37	EL	elm species	970	ULMUS	*Ulmus spp.*
14	38	SI	Siberian elm	974	ULPU	*Ulmus pumila*
14	39	RL	slippery (red) elm	975	ULRU	*Ulmus rubra*
14	40	RE	rock elm	977	ULTH	*Ulmus thomasii*
15	41	YP	yellow-poplar	621	LITU	*Liriodendron tulipifera*
16	42	BW	American basswood	951	TIAM	*Tilia americana*
17	43	SM	sugar maple	318	ACSA3	*Acer saccharum*

Species Group	**Species Number**	**Species Code**	**Common Name**	**FIA Code**	**PLANTS Symbol**	**Scientific Name**
18	44	AS	ash species	540	FRAXI	*Fraxinus spp.*
18	45	WA	white ash	541	FRAM2	*Fraxinus americana*
18	46	GA	green ash	544	FRPE	*Fraxinus pennsylvanica*
19	47	WO	white oak	802	QUAL	*Quercus alba*
20	48	RO	northern red oak	833	QURU	*Quercus rubra*
20	49	SK	southern red oak	812	QUFA	*Quercus falcata*
21	50	BO	black oak	837	QUVE	*Quercus velutina*
22	51	SO	scarlet oak	806	QUCO2	*Quercus coccinea*
23	52	BJ	blackjack oak	824	QUMA3	*Quercus marilandica*
24	53	CK	chinkapin oak	826	QUMU	*Quercus muehlenbergii*
24	54	SW	swamp white oak	804	QUBI	*Quercus bicolor*
24	55	BR	bur oak	823	QUMA2	*Quercus macrocarpa*
24	56	SN	swamp chestnut oak	825	QUMI	*Quercus michauxii*
25	57	PO	post oak	835	QUST	*Quercus stellata*
25	58	DO	delta post oak	836	QUSI2	*Quercus stellata var. paludosa*
26	59	CO	chestnut oak	832	QUPR2	*Quercus prinus*
27	60	PN	pin oak	830	QUPA2	*Quercus palustris*
27	61	CB	cherrybark oak	813	QUPA5	*Quercus pagoda*
27	62	QI	shingle oak	817	QUIM	*Quercus imbricaria*
27	63	OV	overcup oak	822	QULY	*Quercus lyrata*
27	64	WK	water oak	827	QUNI	*Quercus nigra*
27	65	NK	Nuttall oak	828	QUNU	*Quercus nuttallii*
27	66	WL	willow oak	831	QUPH	*Quercus phellos*
27	67	QS	Shumard oak	834	QUSH	*Quercus shumardii*
28	68	UH	other upland hardwoods			
28	69	SS	sassafras	931	SAAL5	*Sassafras albidum*
28	70	OB	Ohio buckeye	331	AEGL	*Aesculus glabra*
28	71	CA	catalpa	450	CATAL	*Catalpa spp.*
28	72	PS	common persimmon	521	DIVI5	*Diospyros virginiana*
28	73	HL	honeylocust	552	GLTR	*Gleditsia triacanthos*
28	74	BP	balsam poplar	741	POBA2	*Populus balsamifera*
28	75	BT	bigtooth aspen	743	POGR4	*Populus grandidentata*
28	76	QA	quaking aspen	746	POTR5	*Populus tremuloides*
28	77	BK	black locust	901	ROPS	*Robinia pseudoacacia*
29	78	OL	other lowland species			
29	79	SY	sycamore	731	PLOC	*Platanus occidentalis*
29	80	BY	baldcypress	221	TADI2	*Taxodium distichum*

Species Group	Species Number	Species Code	Common Name	FIA Code	PLANTS Symbol	Scientific Name
29	81	RB	river birch	373	BENI	*Betula nigra*
29	82	SU	sweetgum	611	LIST2	*Liquidamber styraciflua*
29	83	WI	willow species	920	SALIX	*Salix spp.*
29	84	BL	black willow	922	SANI	*Salix nigra*
30	85	NC	non-commercial hardwoods			
30	86	AH	American hornbeam	391	CACA18	*Carpinus caroliniana*
30	87	RD	eastern redbud	471	CECA4	*Cercis canadensis*
30	88	DW	flowering dogwood	491	COFL2	*Cornus florida*
30	89	HT	hawthorn species	500	CRATA	*Crataegus spp.*
30	90	KC	Kentucky coffeetree	571	GYDI	*Gymnocladus dioicus*
30	91	OO	osage-orange	641	MAPO	*Maclura pomifera*
30	92	CT	cucumbertree	651	MAAC	*Magnolia acuminata*
30	93	MV	sweetbay	653	MAVI2	*Magnolia virginiana*
30	94	MB	mulberry species	680	MORUS	*Morus spp.*
30	95	HH	eastern hophornbeam	701	OSVI	*Ostrya virginiana*
30	96	SD	sourwood	711	OXAR	*Oxydendrum arboreum*

3.3 Habitat Type, Plant Association, and Ecological Unit Codes

Habitat type, plant association, and ecological unit codes are not used in the CS variant.

3.4 Site Index

Site index is used in the growth equations for the CS variant. Users should always use the site index curves from Carmean and others (1989) to estimate site index. In assigning site index, users should use site curves based on total age at an index age of 50. If site index is available, a single site index for the whole stand can be entered, a site index for each individual species in the stand can be entered, or a combination of these can be entered. If site index is missing or incorrect, the site species is set to white oak with a default site index set to 65.

There are no site index conversion equations for the CS variant. Any species for which the species-specific site index is not entered, will be assigned the site index of the site species.

3.5 Maximum Density

Maximum stand density index (SDI) and maximum basal area (BA) are important variables in determining density related mortality and crown ratio change. Maximum basal area is a stand level metric that can be set using the BAMAX or SETSITE keywords. If not set by the user, a default value is calculated from maximum stand SDI each projection cycle. Maximum stand density index can be set for each species using the SDIMAX or SETSITE keywords. If not set by the user, a default value is assigned as discussed below. Maximum stand density index at the stand level is a weighted average, by basal area proportion, of the individual species SDI maximums.

The default maximum SDI is set based on a species basal area maximum or a user specified basal area maximum. If a user specified basal area maximum is present, the maximum SDI for all species is computed using equation {3.5.1}; otherwise, species SDI maximums are assigned from the species basal area maximums shown in table 3.5.1 using equation {3.5.2}.

{3.5.1} $SDIMAX_i = BAMAX / (0.5454154 * SDIU)$

{3.5.2} $SDIMAX_i = BAMAX_i / (0.5454154 * SDIU)$

where:

SDIMAXi	is species-specific SDI maximum
BAMAX	is the user-specified stand basal area maximum
BAMAXi	is species-specific basal area maximum
SDIU	is the proportion of theoretical maximum density at which the stand reaches actual maximum density (default 0.85, changed with the SDIMAX keyword)

Table 3.5.1 Basal area maximums by species in the CS variant.

Species Code	Basal Area Maximum
RC	150
JU	150
SP	210
VP	150
LP	210
OS	150
WP	240
WN	160
BN	150
TL	140
TS	140
WT	140
BG	140
HS	160
SH	160
SL	160
MH	160
PH	160
HI	160
WH	160
BH	160
PE	160
AE	150
SG	150
HK	150
WE	150
EL	150
SI	150
RL	150
RE	150
YP	180
BW	150
SM	150
AS	150
WA	150
GA	150
WO	160
RO	160
SK	160
BO	160
SO	160
BJ	130
CK	160
SW	160
NK	160
WL	160
QS	160
UH	150
SS	150
OB	150
CA	150
PS	150
HL	150
BP	150
BT	130
QA	130
BK	150
OL	150
SY	150
BY	160
RB	150
SU	140
WI	150
BL	150
NC	150
AH	150

Species Code	Basal Area Maximum
BI	160
AB	150
BA	150
PA	150
UA	150
EC	130
RM	150
BE	150
SV	150
BC	200

Species Code	Basal Area Maximum
BR	160
SN	160
PO	130
DO	160
CO	160
PN	160
CB	130
QI	160
OV	160
WK	160

Species Code	Basal Area Maximum
RD	150
DW	150
HT	170
KC	150
OO	150
CT	180
MV	150
MB	150
HH	150
SD	150

4.0 Growth Relationships

This chapter describes the functional relationships used to fill in missing tree data and calculate incremental growth. In FVS, trees are grown in either the small tree sub-model or the large tree sub-model depending on the diameter.

4.1 Height-Diameter Relationships

Height-diameter relationships are used to estimate tree heights missing in the input data and periodic small-tree diameter growth. In the CS variant, height is estimated using either the Curtis-Arney equation (Curtis 1967, Arney 1985) or the Wykoff equation (Wykoff and others 1982) depending on species and depending on whether calibration of the height-diameter relationship for a species occurs. The Wykoff equation form is calibrated to the input data, and subsequently used, for any species that has at least three measured heights, unless calibration of the height-diameter equation is turned off for that species using the NOHTDREG keyword record. Species for which calibration has not occurred use either the Curtis-Arney form or Wykoff form depending on the species. This is indicated by a C or W, respectively, in the third column of table 4.1.1.

The functional form of the Curtis-Arney equation for trees three inches dbh and larger is shown in equation {4.1.1}. For trees less than three inches dbh using the Curtis-Arney equation, a modified Curtis-Arney equation combined with a simple linear equation is used. The functional form of the Wykoff equation is shown in equation {4.1.2}. Equation coefficients and which equation is used for which species when calibration does not occur are shown in table 4.1.1.

{4.1.1} Curtis-Arney equation

$DBH \geq 3.0'': HT = 4.5 + P_2 * \exp(-P_3 * DBH \wedge P_4)$

$DBH < 3.0'': HT = ((4.5 + P_2 * \exp(-P_3 * 3.0 \wedge P_4) - 4.51) * (DBH - D_{bw}) / (3 - D_{bw})) + 4.51$

{4.1.2}Wykoff functional form

$HT = 4.5 + \exp(B_1 + B_2 / (DBH + 1.0))$

where:

HT	is tree height
DBH	is tree diameter at breast height
D_{bw}	is bud width diameter at 4.51 feet shown in table 4.1.1
B_1 - B_2	are species-specific coefficients shown in table 4.1.1
P_2 - P_4	are species-specific coefficients shown in table 4.1.2

Coefficients for the height-diameter relationships in the CS variant are from equations fit to data for the Southern variant of FVS. Wykoff and Curtis-Arney coefficients for all species, are shown in table 4.1.1. Species for which there was not enough data to fit these relationships use coefficients from a similar species.

Table 4.1.1 Coefficients, default equation used, and surrogate species for height-diameter relationships for the CS variant.

Species Code	W or C	SN Variant Surrogate / source	Curtis-Arney Coefficients				Wykoff Coefficients	
			P_2	P_3	P_4	D_{bw}	Default B_1	B_2
RC	W	Virginia pine	926.1803	4.4621	-0.2005	0.5	4.4718	-5.0078
JU	W	juniper species	212.7933	3.4715	-0.3259	0.3	4.0374	-4.2964
SP	W	shortleaf pine	444.0922	4.1188	-0.3062	0.5	4.6271	-6.4095
VP	W	Virginia pine	926.1803	4.4621	-0.2005	0.5	4.4718	-5.0078
LP	W	loblolly pine	243.8606	4.2846	-0.4713	0.5	4.6897	-6.8801
OS	W	juniper species	212.7933	3.4715	-0.3259	0.3	4.0374	-4.2964
WP	C	eastern white pine	2108.8442	5.6595	-0.1856	0.4	4.6090	-6.1896
WN	W	black walnut	93.7104	3.6575	-0.8825	0.4	4.5018	-5.6123
BN	W	butternut	285.8798	3.5214	-0.3194	0.3	4.5018	-5.6123
TL	W	blackgum / black tupelo	319.9788	3.6731	-0.3065	0.2	4.3802	-4.7903
TS	W	swamp tupelo	252.3567	3.2440	-0.3334	0.2	4.4334	-4.5709
WT	W	water tupelo	163.9728	2.7682	-0.4410	0.2	4.4330	-4.5383
BG	C	blackgum / black tupelo	319.9788	3.6731	-0.3065	0.2	4.3802	-4.7903
HS	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
SH	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
SL	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
MH	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
PH	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
HI	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
WH	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
BH	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
PE	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
BI	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
AB	W	American beech	526.1393	3.8923	-0.2259	0.1	4.4772	-4.7206
BA	W	black ash	178.9308	4.9286	-0.6378	0.2	4.6155	-6.2945
PA	W	ash species	251.4043	3.2692	-0.3591	0.2	4.4819	-4.5314
UA	W	ash species	251.4043	3.2692	-0.3591	0.2	4.4819	-4.5314
EC	W	cottonwood	190.9797	3.6928	-0.5273	0.1	4.9396	-8.1838
RM	W	red maple	268.5564	3.1143	-0.2941	0.2	4.3379	-3.8214
BE	W	butternut	285.8798	3.5214	-0.3194	0.3	4.5018	-5.6123
SV	C	silver maple	80.5118	26.9833	-2.0220	0.2	4.5991	-6.6706
BC	W	black cherry	364.0248	3.5599	-0.2726	0.1	4.3286	-4.0922
AE	W	American elm	418.5942	3.1704	-0.1896	0.1	4.6008	-7.2732

			Curtis-Arney Coefficients				**Wykoff Coefficients**	
Species Code	**W or C**	**SN Variant Surrogate / source**	**P_2**	**P_3**	**P_4**	**D_{bw}**	**Default B_1**	**B_2**
SG	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
HK	C	hackberry species	484.7530	3.9393	-0.2600	0.1	4.4207	-5.1435
WE	W	winged elm	1001.6729	4.5731	-0.1890	0.1	4.5992	-7.7428
EL	W	elm species	1005.8067	4.6474	-0.2034	0.1	4.3744	-4.5257
SI	W	elm species	1005.8067	4.6474	-0.2034	0.1	4.3744	-4.5257
RL	W	slippery elm	1337.5472	4.4895	-0.1475	0.1	4.6238	-7.4847
RE	W	elm species	1005.8067	4.6474	-0.2034	0.1	4.3744	-4.5257
YP	C	yellow-poplar	625.7697	3.8732	-0.2335	0.2	4.6892	-4.9605
BW	W	basswood	293.5715	3.5226	-0.3512	0.1	4.5820	-5.0903
SM	W	sugar maple	209.8555	2.9528	-0.3679	0.2	4.4834	-4.5431
AS	W	ash species	251.4043	3.2692	-0.3591	0.2	4.4819	-4.5314
WA	W	white ash	91.3528	6.9961	-1.2294	0.2	4.5959	-6.4497
GA	W	green ash	404.9692	3.3902	-0.2551	0.2	4.6155	-6.2945
WO	W	white oak	170.1331	3.2782	-0.4874	0.2	4.5463	-5.2287
RO	W	northern red oak	700.0636	4.1061	-0.2139	0.2	4.5202	-4.8896
SK	W	southern red oak	150.4300	3.1327	-0.4993	0.1	4.5142	-5.2205
BO	W	black oak	224.7163	3.1165	-0.3598	0.2	4.4747	-4.8698
SO	W	scarlet oak	196.0565	3.0067	-0.3850	0.2	4.5225	-4.9401
BJ	W	blackjack oak	157.4829	3.3892	-0.3915	0.2	3.9191	-4.3503
CK	W	chinkapin oak	72.7907	3.6707	-1.0988	0.1	4.3420	-5.1193
SW	W	cherrybark oak	182.6306	3.1290	-0.4639	0.1	4.7342	-6.2674
BR	W	scarlet oak	196.0565	3.0067	-0.3850	0.2	4.5225	-4.9401
SN	W	swamp chestnut oak	281.3413	3.5170	-0.3336	0.2	4.6135	-5.7613
PO	W	post oak	765.2908	4.2238	-0.1897	0.1	4.2496	-4.8061
DO	W	post oak	765.2908	4.2238	-0.1897	0.1	4.2496	-4.8061
CO	W	chestnut oak	94.5447	3.4203	-0.8188	0.2	4.4618	-4.8786
PN	W	scarlet oak	196.0565	3.0067	-0.3850	0.2	4.5225	-4.9401
CB	W	cherrybark oak	182.6306	3.1290	-0.4639	0.1	4.7342	-6.2674
QI	W	chestnut oak	94.5447	3.4203	-0.8188	0.2	4.4618	-4.8786
OV	W	overcup oak	184.0856	3.4954	-0.4621	0.2	4.5710	-6.0922
WK	W	water oak	470.0617	3.7889	-0.2512	0.1	4.5577	-4.9595
NK	W	scarlet oak	196.0565	3.0067	-0.3850	0.2	4.5225	-4.9401
WL	W	cottonwood	190.9797	3.6928	-0.5273	0.1	4.9396	-8.1838
QS	W	Shumard oak	215.0009	3.1420	-0.3907	0.1	4.6106	-5.4380
UH	W	white oak	170.1331	3.2782	-0.4874	0.2	4.5463	-5.2287
SS	C	sassafras	755.1038	4.3950	-0.2178	0.1	4.3383	-4.5018
OB	W	basswood	293.5715	3.5226	-0.3512	0.1	4.5820	-5.0903

Species Code	W or C	SN Variant Surrogate / source	Curtis-Arney Coefficients				Wykoff Coefficients	
			P_2	P_3	P_4	D_{bw}	Default B_1	B_2
CA	W	catalpa	190.9797	3.6928	-0.5273	0.3	4.9396	-8.1838
PS	W	hackberry species	484.7530	3.9393	-0.2600	0.1	4.4207	-5.1435
HL	W	honeylocust	778.9357	4.2076	-0.1873	0.1	4.3734	-5.3135
BP	W	white ash	91.3528	6.9961	-1.2294	0.2	4.5959	-6.4497
BT	W	white ash	91.3528	6.9961	-1.2294	0.2	4.5959	-6.4497
QA	W	hickory species	337.6685	3.6273	-0.3208	0.3	4.5128	-4.9918
BK	C	black locust	880.2845	4.5964	-0.2182	0.1	4.4299	-4.9920
OL	W	red maple	268.5564	3.1143	-0.2941	0.2	4.3379	-3.8214
SY	W	sycamore	644.3568	3.9205	-0.2144	0.1	4.6355	-5.2776
BY	W	baldcypress	119.5749	4.1354	-0.7963	0.2	4.6171	-6.2684
RB	W	birch species	170.5253	2.6883	-0.4008	0.1	4.4388	-4.0872
SU	W	sweetgum	290.9055	3.6240	-0.3720	0.2	4.5920	-5.1719
WI	W	willow	408.2772	3.8181	-0.2721	0.1	4.4911	-5.7928
BL	W	willow	408.2772	3.8181	-0.2721	0.1	4.4911	-5.7928
NC	W	hackberry species	484.7530	3.9393	-0.2600	0.1	4.4207	-5.1435
AH	C	eastern hophornbeam	109.7324	2.2503	-0.4130	0.2	4.0322	-3.0833
RD	W	eastern redbud	103.1768	2.2170	-0.3596	0.2	3.7512	-2.5539
DW	W	flowering dogwood	863.0501	4.3856	-0.1481	0.1	3.7301	-2.7758
HT	W	hackberry species	484.7530	3.9393	-0.2600	0.1	4.4207	-5.1435
KC	W	American beech	526.1393	3.8923	-0.2259	0.1	4.4772	-4.7206
OO	W	eastern hophornbeam	109.7324	2.2503	-0.4130	0.2	4.0322	-3.0833
CT	C	cucumbertree	660.1997	3.9208	-0.2112	0.2	4.6067	-5.2030
MV	W	sweetbay	184.1932	2.8457	-0.3695	0.2	4.3609	-4.1423
MB	W	mulberry species	750.1823	4.1426	-0.1594	0.2	3.9613	-3.1993
HH	W	eastern hophornbeam	109.7324	2.2503	-0.4130	0.2	4.0322	-3.0833
SD	W	sourwood	690.4918	4.1598	-0.1861	0.2	4.1352	-3.7450

4.2 Bark Ratio Relationships

Bark ratio estimates are used to convert between diameter outside bark and diameter inside bark in various parts of the model. The equation is shown in equation {4.2.1} and the appropriate bark ratios by species group are given in table 4.2.1.

{4.2.1} $DIB = BRATIO * DOB$

where:

BRATIO	is species-specific bark ratio
DIB	is tree diameter inside bark at breast height
DOB	is tree diameter outside bark at breast height

Table 4.2.1 Bark ratios by species groups for the CS variant.

Species Groups	Bark Ratio
4, 5, 11, 20, 21	.91
2, 3, 7, 8, 9, 14, 16, 17, 18, 19, 22, 23, 24, 25, 26, 27, 28, 29	.93
1, 6, 10, 12, 13, 15, 30	.95

4.3 Crown Ratio Relationships

Crown ratio equations are used for three purposes in FVS: (1) to estimate tree crown ratios missing from the input data for both live and dead trees; (2) to estimate change in crown ratio from cycle to cycle for live trees; and (3) to estimate initial crown ratios for regenerating trees established during a simulation.

4.3.1 Crown Ratio Dubbing

In the CS variant, crown ratios missing in the input data, for both live and dead trees, are predicted using equation {4.3.1.1} by Holdaway (1986) with coefficients for this equation shown in table 4.3.1.1.

{4.3.1.1} $CR = 10 * (b_1 / (1 + b_2 * BA) + (b_3 * (1 – \exp(-b_4 * DBH))))$

where:

CR	is crown ratio expressed as a percent
BA	is total stand basal area
DBH	is tree diameter at breast height
$b_1 – b_4$	are species-specific coefficients shown in table 4.3.1.1

Table 4.3.1.1 Coefficients of the crown ratio equation {4.3.1.1} in the CS variant.

Species Group	b_1	b_2	b_3	b_4
1	4.0862	0.0096	4.2295	-0.6554
2, 3, 4	3.8229	0.0155	3.6700	-0.0931
5	5.3258	0.0059	187.8644	-0.0003
6	3.5960	0.0241	3.3785	-0.5607
7, 8	4.0007	0.0132	3.2411	-1.0554
9	3.7332	0.0040	3.6321	-0.0412
10	4.7419	0.0748	3.3270	-0.8711
11	4.5860	0.0045	4.2754	-0.0194
12	4.7334	0.0051	1.5490	-0.1920
13	3.7332	0.0040	3.6321	-0.0412
14	4.2114	0.0006	2.4917	-0.0266
15,16	3.7332	0.0040	3.6321	-0.0412
17	4.5228	0.0049	2.3243	-0.2289
18	4.7419	0.0748	3.3270	-0.8711
19	4.6207	0.0042	2.6272	-0.1684
20	4.6941	0.0057	2.0465	-0.2326

Species Group	b_1	b_2	b_3	b_4
21	5.6002	0.0072	1.7133	-0.1663
22	4.1573	0.0105	2.6185	-0.4623
23	3.6371	0.0096	3.0584	-0.6048
24	4.1897	0.0090	3.3907	-0.1566
25	3.6936	0.0039	2.7332	-0.2339
26	5.8825	0.0082	332.9834	-0.0002
27	1.9729	0.0374	5.3150	-1.0758
28	3.7332	0.0040	3.6321	-0.0412
29	4.5860	0.0045	4.2754	-0.0194
30	4.3510	0.0015	110.6709	-0.0015

4.3.2 Crown Ratio Change

Crown ratio change is estimated after growth, mortality and regeneration are estimated during a projection cycle. Crown ratio change is the difference between the crown ratio at the beginning of the cycle and the predicted crown ratio at the end of the cycle. Crown ratio predicted at the end of the projection cycle is estimated for live tree records using equation {4.3.1.1} by Holdaway (1986) and the coefficients shown in Table 4.3.1.1. Crown change is checked to make sure it doesn't exceed the change possible if all height growth produces new crown. Crown change is further bounded to 1% per year for the length of the cycle to avoid drastic changes in crown ratio.

4.3.3 Crown Ratio for Newly Established Trees

Crown ratios for newly established trees during regeneration are estimated using equation {4.3.3.1}. A random component is added in equation {4.3.3.1} to ensure that not all newly established trees are assigned exactly the same crown ratio.

{4.3.3.1} $CR = 0.89722 - 0.0000461 * PCCF + RAN$

where:

CR	is crown ratio expressed as a proportion (bounded to $0.2 \leq CR \leq 0.9$)
PCCF	is crown competition factor on the inventory point where the tree is established
RAN	is a small random component

4.4 Crown Width Relationships

The CS variant calculates the maximum crown width for each individual tree based on individual tree and stand attributes. Crown width for each tree is reported in the tree list output table and used to calculate percent canopy cover (*PCC*) and crown competition factor (*CCF*) within the model. When available, forest-grown maximum crown width equations are used to compute *PCC* and open-grown maximum crown width equations are used to compute *CCF*.

The CS variant computes tree crown width using equations {4.4.1} through {4.4.5}. Species equation assignment and coefficients are shown in tables 4.4.1 and 4.4.2 for forest- and open-grown equations, respectively. Equations are numbered via the FIA species code and equation number, i.e. the forest grown equation from Bechtold (2003) assigned to Eastern white pine has the number: 12901.

{4.4.1} Bechtold (2003); Equation 01

$DBH \geq 5.0$: $FCW = a_1 + (a_2 * DBH) + (a_3 * DBH^2) + (a_4 * CR) + (a_5 * HI)$

$DBH < 5.0$: $FCW = [a_1 + (a_2 * 5.0) + (a_3 * 5.0^2) + (a_4 * CR) + (a_5 * HI)] * (DBH / 5.0)$

{4.4.2} Bragg (2001); Equation 02

$DBH \geq 5.0$: $FCW = a_1 + (a_2 * DBH^{a_3})$

$DBH < 5.0$: $FCW = [a_1 + (a_2 * 5.0^{a_3})] * (DBH / 5.0)$

{4.4.3} Ek (1974); Equation 03

$DBH \geq 3.0$: $OCW = a_1 + (a_2 * DBH^{a_3})$

$DBH < 3.0$: $OCW = [a_1 + (a_2 * 3.0^{a_3})] * (DBH / 3.0)$

{4.4.4} Krajicek and others (1961); Equation 04

$DBH \geq 3.0$: $OCW = a_1 + (a_2 * DBH)$

$DBH < 3.0$: $OCW = [a_1 + (a_2 * 3.0)] * (DBH / 3.0)$

{4.4.5} Smith and others (1992); Equation 05

$DBH \geq 3.0$: $OCW = a_1 + (a_2 * DBH * 2.54) + (a_3 * (DBH * 2.54)^2) * 3.28084$

$DBH < 3.0$: $OCW = [a_1 + (a_2 * 3.0 * 2.54) + (a_3 * (3.0 * 2.54)^2) * 3.28084] * (DBH / 3.0)$

where:

FCW	is crown width of forest grown trees (used in *PCC* calculations)
OCW	is crown width of open-grown trees (used in *CCF* calculations))
DBH	is tree diameter at breast height, if bounded
CR	is crown ratio expressed as a percent
HI	is the Hopkins Index $HI = (ELEVATION - 887) / 100) * 1.0 + (LATITUDE - 39.54) * 4.0 + (-82.52 - LONGITUDE) * 1.25$
a_1 - a_5	are the coefficients shown in tables 4.4.1 and 4.4.2

Table 4.4.1. Crown width equation assignment and coefficients for forest-grown trees in the CS variant.

Species Code	Equation Number[1]	a_1	a_2	a_3	a_4	a_5	Limits and Bounds
RC	06801	1.2359	1.2962		0.0545		$FCW \leq 33$
JU	06801	1.2359	1.2962		0.0545		$FCW \leq 33$
SP	11001	-2.2564	1.3004		0.1031	-0.0562	$FCW \leq 34$
VP	13201	-0.1211	1.2319		0.1212		$FCW \leq 34$
LP	13101	-0.8277	1.3946		0.0768		$FCW \leq 55$
OS	06801	1.2359	1.2962		0.0545		$FCW \leq 33$
WP	12901	0.3914	0.9923		0.1080		$FCW \leq 45$

Species Code	**Equation Number[1]**	**a_1**	**a_2**	**a_3**	**a_4**	**a_5**	**Limits and Bounds**
WN	60201	3.6031	1.1472		0.1224		FCW ≤ 37
BN	60201	3.6031	1.1472		0.1224		FCW ≤ 37
TL	69301	5.5037	1.0567		0.0880	0.0610	FCW ≤ 50
TS	69401	1.3564	1.0991		0.1243		FCW ≤ 41
WT	69101	5.3409	0.7499		0.1047		FCW ≤ 37
BG	69301	5.5037	1.0567		0.0880	0.0610	FCW ≤ 50
HS	40701	4.5453	1.3721		0.0430		FCW ≤ 54
SH	40701	4.5453	1.3721		0.0430		FCW ≤ 54
SL	40701	4.5453	1.3721		0.0430		FCW ≤ 54
MH	40901	1.5838	1.6318		0.0721		FCW ≤ 55
PH	40301	3.9234	1.5220		0.0405		FCW ≤ 53
HI	40701	4.5453	1.3721		0.0430		FCW ≤ 54
WH	40201	8.0118	1.4212				FCW ≤ 41
BH	40201	8.0118	1.4212				FCW ≤ 41
PE	40201	8.0118	1.4212				FCW ≤ 41
BI	40801	-5.8749	4.1555	-0.1343			DBH ≤ 15
AB	53101	3.9361	1.1500		0.1237	-0.0691	FCW ≤ 80
BA	54301	5.2824	1.1184				FCW ≤ 34
PA	54101	1.7625	1.3413		0.0957		FCW ≤ 62
UA	54101	1.7625	1.3413		0.0957		FCW ≤ 62
EC	74201	3.4375	1.4092				FCW ≤ 80
RM	31601	2.7563	1.4212	-0.0143	0.0993	-0.0276	DBH ≤ 50
BE	31301	6.4741	1.0778		0.0719	-0.0637	FCW ≤ 57
SV	31701	3.3576	1.1312		0.1011	-0.1730	FCW ≤ 45
BC	76201	3.0237	1.1119		0.1112	-0.0493	FCW ≤ 52
AE	97201	1.7296	2.0732		0.0590	-0.0869	FCW ≤ 50
SG	46201	7.1043	1.3041		0.0456		FCW ≤ 51
HK	46201	7.1043	1.3041		0.0456		FCW ≤ 51
WE	97101	4.3649	1.6612		0.0643		FCW ≤ 40
EL	97201	1.7296	2.0732		0.0590	-0.0869	FCW ≤ 50
SI	97201	1.7296	2.0732		0.0590	-0.0869	FCW ≤ 50
RL	97501	9.0023	1.3933			-0.0785	FCW ≤ 49
RE	97201	1.7296	2.0732		0.0590	-0.0869	FCW ≤ 50
YP	62101	3.3543	1.1627		0.0857		FCW ≤ 61
BW	95101	1.6871	1.2110		0.1194	-0.0264	FCW ≤ 61
SM	31801	4.9399	1.0727		0.1096	-0.0493	FCW ≤ 54
AS	54401	2.9672	1.3066		0.0585		FCW ≤ 61
WA	54101	1.7625	1.3413		0.0957		FCW ≤ 62
GA	54401	2.9672	1.3066		0.0585		FCW ≤ 61
WO	80201	3.2375	1.5234		0.0455	-0.0324	FCW ≤ 69

Species Code	Equation Number[1]	a_1	a_2	a_3	a_4	a_5	Limits and Bounds
RO	83301	2.8908	1.4077		0.0643		FCW ≤ 82
SK	81201	2.1517	1.6064		0.0609		FCW ≤ 56
BO	83701	2.8974	1.3697		0.0671		FCW ≤ 52
SO	80601	0.5656	1.6766		0.0739		FCW ≤ 66
BJ	82401	0.5443	1.4882		0.0565		FCW ≤ 37
CK	82601	0.5189	1.4134		0.1365	-0.0806	FCW ≤ 45
SW	80201	3.2375	1.5234		0.0455	-0.0324	FCW ≤ 69
BR	82301	1.7827	1.6549		0.0343		FCW ≤ 61
SN	83201	2.1480	1.6928	-0.0176	0.0569		DBH ≤ 50
PO	83501	1.6125	1.6669		0.0536		FCW ≤ 45
DO	83501	1.6125	1.6669		0.0536		FCW ≤ 45
CO	83201	2.1480	1.6928	-0.0176	0.0569		DBH ≤ 50
PN	83001	-5.6268	1.7808		0.1231	0.1578	FCW ≤ 63
CB	81201	2.1517	1.6064		0.0609		FCW ≤ 56
QI	81701	9.8187	1.1343				FCW ≤ 54
OV	82301	1.7827	1.6549		0.0343		FCW ≤ 61
WK	82701	1.6349	1.5443		0.0637	-0.0764	FCW ≤ 57
NK	81201	2.1517	1.6064		0.0609		FCW ≤ 56
WL	83101	1.6477	1.3672		0.0846		FCW ≤ 74
QS	81201	2.1517	1.6064		0.0609		FCW ≤ 56
UH	93101	4.6311	1.0108		0.0564		FCW ≤ 29
SS	93101	4.6311	1.0108		0.0564		FCW ≤ 29
OB	40701	4.5453	1.3721		0.0430		FCW ≤ 54
CA	93101	4.6311	1.0108		0.0564		FCW ≤ 29
PS	52101	3.5393	1.3939		0.0625		FCW ≤ 36
HL	55201	4.1971	1.5567		0.0880		FCW ≤ 46
BP	74101	6.2498	0.8655				FCW ≤ 25
BT	74301	0.6847	1.1050		0.1420	-0.0265	FCW ≤ 43
QA	74601	0.7315	1.3180		0.0966		FCW ≤ 39
BK	90101	3.0012	0.8165		0.1395		FCW ≤ 48
OL	73101	-1.3973	1.3756		0.1835		FCW ≤ 66
SY	73101	-1.3973	1.3756		0.1835		FCW ≤ 66
BY	22101	-1.0183	0.8856		0.1162		FCW ≤ 37
RB	37301	11.6634	1.0028				FCW ≤ 68
SU	61101	1.8853	1.1625		0.0656	-0.0300	FCW ≤ 50
WI	97201	1.7296	2.0732		0.0590	-0.0869	FCW ≤ 50
BL	97201	1.7296	2.0732		0.0590	-0.0869	FCW ≤ 50
NC	49101	2.9646	1.9917		0.0707		FCW ≤ 36
AH	39101	0.9219	1.6303		0.1150	-0.1113	FCW ≤ 42
RD	49101	2.9646	1.9917		0.0707		FCW ≤ 36

Species Code	Equation Number[1]	a_1	a_2	a_3	a_4	a_5	Limits and Bounds
DW	49101	2.9646	1.9917		0.0707		FCW ≤ 36
HT	49101	2.9646	1.9917		0.0707		FCW ≤ 36
KC	90101	3.0012	0.8165		0.1395		FCW ≤ 48
OO	93101	4.6311	1.0108		0.0564		FCW ≤ 29
CT	65101	4.1711	1.6275				FCW ≤ 39
MV	65301	8.2119	0.9708				FCW ≤ 41
MB	68201	13.3255	1.0735				FCW ≤ 46
HH	70101	7.8084	0.8129		0.0941	-0.0817	FCW ≤ 39
SD	71101	7.9750	0.8303		0.0423	-0.0706	FCW ≤ 36

[1] Equation number is a combination of the species FIA code (###) and source (##), see equations on previous page. Maximum crown widths and DBH have been assigned to prevent poor behavior beyond the source data.

Table 4.4.2. Crown width equation assignment and coefficients for open-grown trees for the CS variant.

Species Code	Equation Number[1]	a_1	a_2	a_3	a_4	a_5	Limits and Bounds
RC	06801	1.2359	1.2962		0.0545		FCW ≤ 33
JU	06801	1.2359	1.2962		0.0545		FCW ≤ 33
SP	11005	0.5830	0.2450	0.0009			FCW ≤ 45
VP	13201	-0.1211	1.2319		0.1212		FCW ≤ 34
LP	13105	0.7380	0.2450	0.000809			FCW ≤ 66
OS	06801	1.2359	1.2962		0.0545		FCW ≤ 33
WP	12903	1.6200	3.1970	0.7981			FCW ≤ 58
WN	60201	3.6031	1.1472		0.1224		FCW ≤ 37
BN	60201	3.6031	1.1472		0.1224		FCW ≤ 37
TL	69301	5.5037	1.0567		0.0880	0.0610	FCW ≤ 50
TS	69401	1.3564	1.0991		0.1243		FCW ≤ 41
WT	69101	5.3409	0.7499		0.1047		FCW ≤ 37
BG	69301	5.5037	1.0567		0.0880	0.0610	FCW ≤ 50
HS	40703	2.3600	3.5480	0.7986			FCW ≤ 54
SH	40703	2.3600	3.5480	0.7986			FCW ≤ 54
SL	40703	2.3600	3.5480	0.7986			FCW ≤ 54
MH	40901	1.5838	1.6318		0.0721		FCW ≤ 55
PH	40301	3.9234	1.5220		0.0405		FCW ≤ 53
HI	40703	2.3600	3.5480	0.7986			FCW ≤ 54
WH	40201	8.0118	1.4212				FCW ≤ 41
BH	40201	8.0118	1.4212				FCW ≤ 41
PE	40201	8.0118	1.4212				FCW ≤ 41
BI	40801	-5.8749	4.1555	-0.1343			DBH ≤ 15
AB	53101	3.9361	1.1500		0.1237	-0.0691	FCW ≤ 80

Species Code	Equation Number[1]	a_1	a_2	a_3	a_4	a_5	Limits and Bounds
BA	54301	5.2824	1.1184				FCW ≤ 34
PA	54101	1.7625	1.3413		0.0957		FCW ≤ 62
UA	54101	1.7625	1.3413		0.0957		FCW ≤ 62
EC	74203	2.9340	2.5380	0.8617			FCW ≤ 80
RM	31603	0.00	4.7760	0.7656			FCW ≤ 55
BE	31301	6.4741	1.0778		0.0719	-0.0637	FCW ≤ 57
SV	31701	3.3576	1.1312		0.1011	-0.1730	FCW ≤ 45
BC	76203	0.6210	7.0590	0.5441			FCW ≤ 52
AE	97203	2.8290	3.4560	0.8575			FCW ≤ 72
SG	46201	7.1043	1.3041		0.0456		FCW ≤ 51
HK	46201	7.1043	1.3041		0.0456		FCW ≤ 51
WE	97101	4.3649	1.6612		0.0643		FCW ≤ 40
EL	97203	2.8290	3.4560	0.8575			FCW ≤ 72
SI	97203	2.8290	3.4560	0.8575			FCW ≤ 72
RL	97501	9.0023	1.3933			-0.0785	FCW ≤ 49
RE	97203	2.8290	3.4560	0.8575			FCW ≤ 72
YP	62101	3.3543	1.1627		0.0857		FCW ≤ 61
BW	95101	1.6871	1.2110		0.1194	-0.0264	FCW ≤ 61
SM	31803	0.8680	4.1500	0.7514			FCW ≤ 54
AS	54403	0.0000	4.7550	0.7381			FCW ≤ 61
WA	54101	1.7625	1.3413		0.0957		FCW ≤ 62
GA	54403	0.0000	4.7550	0.7381			FCW ≤ 61
WO	80204	1.8000	1.8830				FCW ≤ 69
RO	83303	2.8500	3.7820	0.7968			FCW ≤ 82
SK	81201	2.1517	1.6064		0.0609		FCW ≤ 56
BO	83704	4.5100	1.6700				FCW ≤ 52
SO	80601	0.5656	1.6766		0.0739		FCW ≤ 66
BJ	82401	0.5443	1.4882		0.0565		FCW ≤ 37
CK	82601	0.5189	1.4134		0.1365	-0.0806	FCW ≤ 45
SW	80204	1.8000	1.8830				FCW ≤ 69
BR	82303	0.9420	3.5390	0.7952			FCW ≤ 78
SN	83201	2.1480	1.6928	-0.0176	0.0569		DBH ≤ 50
PO	83501	1.6125	1.6669		0.0536		FCW ≤ 45
DO	83501	1.6125	1.6669		0.0536		FCW ≤ 45
CO	83201	2.1480	1.6928	-0.0176	0.0569		DBH ≤ 50
PN	83001	-5.6268	1.7808		0.1231	0.1578	FCW ≤ 63
CB	81201	2.1517	1.6064		0.0609		FCW ≤ 56
QI	81701	9.8187	1.1343				FCW ≤ 54
OV	82303	0.9420	3.5390	0.7952			FCW ≤ 78
WK	82701	1.6349	1.5443		0.0637	-0.0764	FCW ≤ 57

Species Code	Equation Number[1]	a_1	a_2	a_3	a_4	a_5	Limits and Bounds
NK	81201	2.1517	1.6064		0.0609		FCW ≤ 56
WL	83101	1.6477	1.3672		0.0846		FCW ≤ 74
QS	81201	2.1517	1.6064		0.0609		FCW ≤ 56
UH	93101	4.6311	1.0108		0.0564		FCW ≤ 29
SS	93101	4.6311	1.0108		0.0564		FCW ≤ 29
OB	40703	2.3600	3.5480	0.7986			FCW ≤ 54
CA	93101	4.6311	1.0108		0.0564		FCW ≤ 29
PS	52101	3.5393	1.3939		0.0625		FCW ≤ 36
HL	55201	4.1971	1.5567		0.0880		FCW ≤ 46
BP	74101	6.2498	0.8655				FCW ≤ 25
BT	74301	0.6847	1.1050		0.1420	-0.0265	FCW ≤ 43
QA	74603	4.2030	2.1290	1.0000			FCW ≤ 43
BK	90101	3.0012	0.8165		0.1395		FCW ≤ 48
OL	73101	-1.3973	1.3756		0.1835		FCW ≤ 66
SY	73101	-1.3973	1.3756		0.1835		FCW ≤ 66
BY	22101	-1.0183	0.8856		0.1162		FCW ≤ 37
RB	37301	11.6634	1.0028				FCW ≤ 68
SU	61101	1.8853	1.1625		0.0656	-0.0300	FCW ≤ 50
WI	97203	2.8290	3.4560	0.8575			FCW ≤ 72
BL	97203	2.8290	3.4560	0.8575			FCW ≤ 72
NC	49101	2.9646	1.9917		0.0707		FCW ≤ 36
AH	39101	0.9219	1.6303		0.1150	-0.1113	FCW ≤ 42
RD	49101	2.9646	1.9917		0.0707		FCW ≤ 36
DW	49101	2.9646	1.9917		0.0707		FCW ≤ 36
HT	49101	2.9646	1.9917		0.0707		FCW ≤ 36
KC	90101	3.0012	0.8165		0.1395		FCW ≤ 48
OO	93101	4.6311	1.0108		0.0564		FCW ≤ 29
CT	65101	4.1711	1.6275				FCW ≤ 39
MV	65301	8.2119	0.9708				FCW ≤ 41
MB	68201	13.3255	1.0735				FCW ≤ 46
HH	70101	7.8084	0.8129		0.0941	-0.0817	FCW ≤ 39
SD	71101	7.9750	0.8303		0.0423	-0.0706	FCW ≤ 36

[1] Equation number is a combination of the species FIA code (###) and source (##), see equations on previous page. Maximum crown widths and DBH have been assigned to prevent poor behavior beyond the source data.

4.5 Crown Competition Factor

The CS variant uses crown competition factor (*CCF*) as a predictor variable in some growth relationships. Crown competition factor (Krajicek and others 1961) is a relative measurement of stand density that is based on tree diameters. Individual tree CCF_t values estimate the percentage of an acre that would be covered by the tree’s crown if the tree were open-grown. Stand *CCF* is the summation of individual tree (CCF_t) values. A stand *CCF* value of 100 theoretically indicates that tree crowns will just touch in an unthinned, evenly spaced stand. In the CS variant, crown competition factor for an individual tree is calculated using equation {4.5.1}, and is based on crown width of open-grown trees.

{4.5.1} All species

$DBH > 0.1''$: $CCF_t = 0.001803 * OCW_t$^2

$DBH \leq 0.1''$: $CCF_t = 0.001$

where:

CCF_t	is crown competition factor for an individual tree
OCW_t	is open-grown crown width for an individual tree
DBH	is tree diameter at breast height

4.6 Small Tree Growth Relationships

Trees are considered “small trees” for FVS modeling purposes when they are smaller than some threshold diameter. This threshold diameter is set to 5.0” for all species in the CS variant.

The small tree model is height growth driven, meaning height growth is estimated first and diameter growth is estimated from height growth. These relationships are discussed in the following sections.

FVS blends small tree growth estimates with large tree growth estimates to assure a smooth transition between the two models. In the CS variant both height growth and diameter growth estimates use this blending technique. Small and large tree estimates are weighted over the diameter range 1.5”-5.0” *DBH* for all species. The weight is calculated using equation {4.6.1} and applied as shown in equation {4.6.2}.

{4.6.1}

$DBH \leq 1.5''$: $XWT = 0$
$1.5'' < DBH < 5.0''$: $XWT = (DBH - 1.5) / (5.0 - 1.5)$
$DBH \geq 5.0''$: $XWT = 1$

{4.6.2} Estimated growth = $[(1 - XWT) * STGE] + [XWT * LTGE]$

where:

XWT	is the weight applied to the growth estimates
DBH	is tree diameter at breast height
STGE	is the growth estimate obtained using the small-tree growth model
LTGE	is the growth estimate obtained using the large-tree growth model

For example, the closer a tree's *DBH* value is to the minimum diameter of 1.5", the more the growth estimate will be weighted towards the small-tree growth model estimate. The closer a tree's *DBH* value is to the maximum diameter of 5.0", the more the growth estimate will be weighted towards the large-tree growth model estimate. If a tree's *DBH* value falls outside of the range 1.5" – 5.0", then only the small-tree or large-tree growth model estimate is used.

4.6.1 Small Tree Height Growth

Small tree height growth is estimated by calculating a potential height growth and modifying the estimate based on intra-stand competition. The estimate is then adjusted by cycle length, scaling factors computed by FVS based on the input small-tree height increment data, and any growth multipliers entered by the user. Potential height growth and the modifier value are estimated using the same equations described in section 4.7.2 to calculate large tree height growth. However, the scaling factor, 0.8, shown in equation {4.7.2.3} is not applied when estimating small tree height growth. Small tree height growth estimates are weighted with large tree height growth estimates as described above.

4.6.2 Small Tree Diameter Growth

Small tree diameter increment is estimated using the height-diameter relationships discussed in section 4.1. The functions are algebraically solved to estimate diameter as a function of height. Height at the start of the projection cycle is known. Height at the end of the projection cycle is obtained by adding the height growth (section 4.6.1) to the starting height. Diameter is predicted at the start of the projection cycle based on the height at the start of the projection cycle; diameter at the end of the projection cycle is estimated from the height at the end of the projection cycle. Small tree diameter growth is calculated as the difference between the predicted diameter at the start of the projection cycle and predicted diameter at the end of the projection cycle, and adjusted for bark ratio. Small tree diameter growth estimates are weighted with large tree diameter growth estimates as described above.

4.7 Large Tree Growth Relationships

Trees are considered "large trees" for FVS modeling purposes when they are equal to, or larger than, some threshold diameter. This threshold diameter is set to 5.0" for all species in the CS variant.

The large-tree model is driven by diameter growth meaning diameter growth is estimated first, and then height growth is estimated from diameter growth and other variables. These relationships are discussed in the following sections.

4.7.1 Large Tree Diameter Growth

The large tree diameter growth model used in most FVS variants is described in section 7.2.1 in Dixon (2002). For most variants, instead of predicting diameter increment directly, the natural log of the periodic change in squared inside-bark diameter (ln(*DDS*)) is predicted (Dixon 2002; Wykoff 1990; Stage 1973; and Cole and Stage 1972). For variants predicting diameter increment directly, diameter increment is converted to the *DDS* scale to keep the FVS system consistent across all variants.

The CS variant uses a large-tree diameter increment model comprised of two separate parts: a potential growth equation and a competition modifier (USDA Forest Service 1983). Equations included in the diameter increment model are shown in equations {4.7.1.1} – {4.7.1.3}, and coefficients for these equations are shown in tables 4.7.1.1 and 4.7.1.2. Diameter growth is predicted for a one-year period and adjusted to the cycle length.

{4.7.1.1} $PADG = (a_1 * TRBA^{a_2} - a_3 * TRBA) * (a_4 + a_5 * SI + a_6 * CR)$

{4.7.1.2} $CM = b_3 * (1 - \exp(-1.0 * (b_1 / (BAL + TRBA) + b_2 * DBH^2) * (1 - TEMBA / 210)^{0.5}))$

{4.7.1.3} $DG = (PADG * GM)$

where:

PADG	is potential annual diameter growth
TRBA	is tree basal area
DBH	is current tree diameter at breast height
SI	is species site index
CR	is crown ratio class expressed as CR = CR% / 10
CM	is competition modifier (bounded $0.15 \leq CM$)
BAL	is total basal area in trees larger than the subject tree (bounded $1 \leq BAL$)
DG	is the annual diameter growth
TEMBA	is the current stand basal area (bounded $TEMBA \leq 200$)

$a_1 - a_6$, $b_1 - b_3$are species group specific coefficients

Table 4.7.1.1 Coefficients ($a_1 - a_6$) for the potential annual growth equation in the CS variant.

Species Group	a_1	a_2	a_3	a_4	a_5	a_6
1	0.03922	0.51499	0.01486	0.39742	0.00072	0.07491
2, 3, 4	0.03996	0.14593	0.00971	0.82519	0.00048	0.04545
5	0.06447	0.43471	0.01054	0.08016	0.00742	0.08056
6	0.03503	0.49430	0.01475	0.49661	0.00774	0
7, 8	0.05274	0.55320	0.01840	0.42132	0.00535	0.04310
9,13,16,28	0.09306	0.64110	0.03054	0.62209	0	0.08509
10,18	0.06565	0.50860	0.01496	0.72314	0.00031	0.05853
11,29	0.13392	0.54184	0.03073	0.75132	0.00317	0
12	0.16952	0.73000	0.07633	0.49370	0.00578	0.00497
14	0.09366	0.62629	0.03426	0.68951	0.00438	0.00429
15	0.07754	0.59212	0.01618	0.61431	0	0.08771
17	0.04857	0.61582	0.01459	0.85147	0.00111	0.01121
19	0.06090	0.55888	0.01361	0.73498	0.00347	0.00847
20	0.06332	0.59455	0.01595	0.69043	0.00385	0.01173
21	0.07176	0.53297	0.01815	0.79907	0.00204	0.01302
22	0.08797	0.65940	0.04119	0.72584	0.00132	0.03473
23	0.03825	0.54171	0.01367	0.85593	0.00280	0
24	0.03628	0.60465	0.01089	0.20651	0.00690	0.07331
25	0.04509	0.62527	0.02187	0.67032	0.00017	0.05860
26	0.08655	0.69260	0.03688	0.00627	0.01273	0.02657

Species Group	a_1	a_2	a_3	a_4	a_5	a_6
27	0.08102	0.41668	0.01323	0.09305	0.00323	0.11176
30	0.07158	0.64291	0.02943	0.29425	0.00130	0.13964

Table 4.7.1.2 Coefficients (b_1– b_3 for the competition modifier equation in the CS variant.

Species Group	b_1	b_2	b_3
1	78.28314	0.01558	0.63527
2, 3, 4	16.66343	0.00818	0.70245
5	109.46000	0.03178	0.34065
6	44.06346	0.01599	0.52659
7, 8	46.40488	0.01241	0.45019
9,13,16,28	68.77668	0.01420	0.46704
10,18	41.56090	0.04964	0.42627
11,29	53.17666	0.00720	0.40176
12	48.52519	0.10557	0.49498
14	46.11206	0.00869	0.46063
15	0	0.31006	0.64505
17	97.03679	0.02560	0.60090
19	75.41392	0.00679	0.49141
20	115.41287	0.00753	0.62906
21	84.94737	0.00293	0.51575
22	71.64226	0.00261	0.74850
23	44.03164	0.00905	0.70245
24	123.43504	0.04658	0.52519
25	80.00477	0.00808	0.59464
26	66.33843	0.00210	0.58700
27	36.37700	0.00870	0.62321
30	141.34518	0.01370	0.35210

4.7.2 Large Tree Height Growth

The large-tree height growth model also uses the modeling technique of estimating a potential height growth and modifying this potential growth based on tree competition. Potential height growth is estimated using site index curves from Carmean et al (1989). Surrogate curves, based on general growth form for the species, were chosen for species for which curves were not given in Carmean et al. The general form of the equation to estimate height given tree age and site index is shown in equation {4.7.2.1}. Algebraic manipulation to estimate tree age from height and site index yields the equation shown in {4.7.2.2}. Coefficients by species and which of the Carmean et al equations are used for which species are shown in table 4.7.2.1.

{4.7.2.1} $HT = b_6 + b_1 * SI \wedge b_2 * (1 - \exp(b_3 * A)) \wedge (b_4 * SI \wedge b_5)$

{4.7.2.2} $A = 1./b_3*(\ln(1-((HT-b_6)/b_1/SI \wedge b_2) \wedge (1./b_4/SI \wedge b_5)))$

where:

HT is tree height
SI is species site index
A is tree age
$b_1 - b_6$ are coefficients shown in table 4.7.2.1
$b_6 = 0$ for total age curves; $b_6 = 4.5$ for breast-height age curves

First, tree age is estimated using site index and the height of the tree at the beginning of the cycle. Next, age is incremented by 10 years and a new height is estimated using the updated age and site index. The difference between the new estimated height and the tree height at the beginning of the cycle is potential height growth. A small random component is applied to insure some distribution in estimated heights.

Potential height growth gets modified by a combination of two factors. One factor is the same modifier, CM, calculated using equation {4.7.1.2} and applied to large-tree diameter growth. The other is a function of individual tree height relative to the average height of the 40-largest diameter trees in the stand. The potential height growth modifier is shown in equation {4.7.2.3}, and the resulting height growth estimate is shown in equation {4.7.2.4}. Estimated height growth is then adjusted for cycle length and user-supplied growth multipliers.

{4.7.2.3} $PHMOD = [1 - ((1 - CM) * (1 - RELHT))] * 0.8$

{4.7.2.4} $HTG_i = PHTG * PHMOD$

where:

HTG_i	is estimated height growth of an individual tree
$PHTG$	is potential height growth estimated as described above
$PHMOD$	is potential height growth modifier
CM	is growth modifier as described in section 4.7.1
$RELHT$	is tree height divided by average height of the 40 largest diameter trees in the stand

Table 4.7.2.1. Coefficients for site index curves used in the CS variant.

Species Code	Carmean et al Figure	Site Index Curve Coefficients					
		b_1	b_2	b_3	b_4	b_5	b_6
RC	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
JU	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
SP	78	1.4232	0.9989	-0.0285	1.2156	0.0088	0.0
VP	125	0.7716	1.1087	-0.0348	0.1099	0.5274	0.0
LP	110	1.1421	1.0042	-0.0374	0.7632	0.0358	0.0
OS	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
WP	104	3.2425	0.7980	-0.0435	52.0549	-0.7064	0.0
WN	16	1.2898	0.9982	-0.0289	0.8546	0.0171	0.0
BN	16	1.2898	0.9982	-0.0289	0.8546	0.0171	0.0
TL	27	1.3213	0.9995	-0.0254	0.8549	-0.0016	0.0
TS	27	1.3213	0.9995	-0.0254	0.8549	-0.0016	0.0
WT	26	1.2721	0.9995	-0.0256	0.7447	-0.0019	0.0
BG	27	1.3213	0.9995	-0.0254	0.8549	-0.0016	0.0
HS	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
SH	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
SL	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
MH	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
PH	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
HI	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
WH	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
BH	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0

Species Code	Carmean et al Figure	Site Index Curve Coefficients					
		b_1	b_2	b_3	b_4	b_5	b_6
PE	19	1.5932	1.0124	-0.0122	0.6245	0.0130	0.0
BI	10	1.8326	1.0015	-0.0207	1.4080	-0.0005	0.0
AB	11	29.7300	0.3631	-0.0127	16.7616	-0.6804	0.0
BA	14	4.2286	0.7857	-0.0178	4.6219	-0.3591	0.0
PA	15	1.6505	0.9096	-0.0644	125.7045	-0.8908	0.0
UA	12	1.5768	0.9978	-0.0156	0.6705	0.0182	0.0
EC	28	1.3615	0.9813	-0.0675	1.5494	-0.0767	0.0
RM	1	2.9435	0.9132	-0.0141	1.6580	-0.1095	0.0
BE	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
SV	4	1.0645	0.9918	-0.0812	1.5754	-0.0272	0.0
BC	35	7.1846	0.6781	-0.0222	13.9186	-0.5268	0.0
AE	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
SG	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
HK	19	1.5932	1.0124	-0.0122	0.6245	0.0130	0.0
WE	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
EL	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
SI	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
RL	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
RE	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
YP	25	1.2941	0.9892	-0.0315	1.0481	-0.0368	0.0
BW	51	4.7633	0.7576	-0.0194	6.5110	-0.4156	0.0
SM	2	3.3721	0.8407	-0.0150	2.6208	-0.2661	0.0
AS	12	1.5768	0.9978	-0.0156	0.6705	0.0182	0.0
WA	12	1.5768	0.9978	-0.0156	0.6705	0.0182	0.0
GA	15	1.6505	0.9096	-0.0644	125.7045	-0.8908	0.0
WO	41	4.5598	0.8136	-0.0132	2.2410	-0.1880	0.0
RO	38	0.4737	1.2905	-0.0236	0.0979	0.6121	0.0
SK	37	1.2866	0.9962	-0.0355	1.4485	-0.0316	0.0
BO	49	2.9989	0.8435	-0.0200	3.4635	-0.3020	0.0
SO	42	1.6763	0.9837	-0.0220	0.9949	0.0240	0.0
BJ	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
CK	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
SW	44	1.3466	0.9590	-0.0574	8.9538	-0.3454	0.0
BR	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
SN	44	1.3466	0.9590	-0.0574	8.9538	-0.3454	0.0
PO	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
DO	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
CO	46	1.9044	0.9752	-0.0162	0.9262	0.0	0.0
PN	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
CB	43	1.0945	0.9938	-0.0755	2.5601	0.0114	0.0

Species Code	**Carmean et al Figure**	**Site Index Curve Coefficients**					
		b_1	**b_2**	**b_3**	**b_4**	**b_5**	**b_6**
QI	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
OV	45	1.3295	0.9565	-0.0668	16.0085	-0.4157	0.0
WK	44	1.3466	0.9590	-0.0574	8.9538	-0.3454	0.0
NK	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
WL	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
QS	43	1.0945	0.9938	-0.0755	2.5601	0.0114	0.0
UH	36	2.1037	0.9140	-0.0275	3.7962	-0.2530	0.0
SS	50	0.9680	1.0301	-0.0468	0.1639	0.4127	0.0
OB	1	2.9435	0.9132	-0.0141	1.6580	-0.1095	0.0
CA	14	4.2286	0.7857	-0.0178	4.6219	-0.3591	0.0
PS	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
HL	50	0.9680	1.0301	-0.0468	0.1639	0.4127	0.0
BP	25	1.2941	0.9892	-0.0315	1.0481	-0.0368	0.0
BT	32	5.2188	0.6855	-0.0301	50.0071	-0.8695	0.0
QA	32	5.2188	0.6855	-0.0301	50.0071	-0.8695	0.0
BK	50	0.9680	1.0301	-0.0468	0.1639	0.4127	0.0
OL	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
SY	25	1.2941	0.9892	-0.0315	1.0481	-0.0368	0.0
BY	21	1.0902	1.0298	-0.0354	0.7011	0.1178	0.0
RB	5	2.2835	0.9794	-0.0054	0.5819	-0.0281	0.0
SU	19	1.5932	1.0124	-0.0122	0.6245	0.0130	0.0
WI	50	0.9680	1.0301	-0.0468	0.1639	0.4127	0.0
BL	50	0.9680	1.0301	-0.0468	0.1639	0.4127	0.0
NC	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
AH	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
RD	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
DW	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
HT	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
KC	53	6.4362	0.6827	-0.0194	10.9767	-0.5477	0.0
OO	50	0.9680	1.0301	-0.0468	0.1639	0.4127	0.0
CT	25	1.2941	0.9892	-0.0315	1.0481	-0.0368	0.0
MV	27	1.3213	0.9995	-0.0254	0.8549	-0.0016	0.0
MB	16	1.2898	0.9982	-0.0289	0.8546	0.0171	0.0
HH	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0
SD	58	0.9276	1.0591	-0.0424	0.3529	0.3114	0.0

5.0 Mortality Model

The CS variant uses an SDI-based mortality model as described in Section 7.3.2 of Essential FVS: A User's Guide to the Forest Vegetation Simulator (Dixon 2002, referred to as EFVS). This SDI-based mortality model is comprised of two steps: 1) determining the amount of stand mortality (section 7.3.2.1 of EFVS) and 2) dispersing stand mortality to individual tree records (section7.3.2.2 of EFVS). In determining the amount of stand mortality, the summation of individual tree background mortality rates is used when stand density is below the minimum level for density dependent mortality (default is 55% of maximum SDI), while stand level density-related mortality rates are used when stands are above this minimum level.

The equation used to calculate individual tree background mortality rates for all species is shown in equation {5.0.1}, and this is then adjusted to the length of the cycle by using a compound interest formula as shown in equation {5.0.2}. Coefficients for these equations are shown in table 5.0.1. The overall amount of mortality calculated for the stand is the summation of the final mortality rate (*RIP*) across all live tree records.

{5.0.1} $RI = [1 / (1 + \exp(p_0 + p_1 * DBH))] * 0.5$

{5.0.2} $RIP = 1 – (1 – RI)^Y$

where:

RI	is the proportion of the tree record attributed to mortality
RIP	is the final mortality rate adjusted to the length of the cycle
DBH	is tree diameter at breast height
Y	is length of the current projection cycle in years
p_0 and p_1	are species-specific coefficients shown in table 5.0.1

Table 5.0.1 Coefficients used in the background mortality equation {5.0.1} in the CS variant.

Species Code	p_0	p_1
RC	5.5876999	-0.0053480
JU	9.6942997	-0.0127328
SP	5.5876999	-0.0053480
VP	5.5876999	-0.0053480
LP	5.5876999	-0.0053480
OS	9.6942997	-0.0127328
WP	5.5876999	-0.0053480
WN	5.9617000	-0.0340128
BN	5.9617000	-0.0340128
TL	5.1676998	-0.0077681
TS	5.9617000	-0.0340128
WT	5.9617000	-0.0340128
BG	5.1676998	-0.0077681

Species Code	**p_0**	**p_1**
HS	5.9617000	-0.0340128
SH	5.9617000	-0.0340128
SL	5.9617000	-0.0340128
MH	5.9617000	-0.0340128
PH	5.9617000	-0.0340128
HI	5.9617000	-0.0340128
WH	5.9617000	-0.0340128
BH	5.9617000	-0.0340128
PE	5.9617000	-0.0340128
BI	5.9617000	-0.0340128
AB	5.1676998	-0.0077681
BA	5.9617000	-0.0340128
PA	5.1676998	-0.0077681
UA	5.1676998	-0.0077681
EC	5.9617000	-0.0340128
RM	5.1676998	-0.0077681
BE	5.9617000	-0.0340128
SV	5.1676998	-0.0077681
BC	5.9617000	-0.0340128
AE	5.1676998	-0.0077681
SG	5.9617000	-0.0340128
HK	5.9617000	-0.0340128
WE	5.1676998	-0.0077681
EL	5.1676998	-0.0077681
SI	5.1676998	-0.0077681
RL	5.1676998	-0.0077681
RE	5.1676998	-0.0077681
YP	5.9617000	-0.0340128
BW	5.1676998	-0.0077681
SM	5.1676998	-0.0077681
AS	5.1676998	-0.0077681
WA	5.9617000	-0.0340128
GA	5.1676998	-0.0077681
WO	5.9617000	-0.0340128
RO	5.9617000	-0.0340128
SK	5.9617000	-0.0340128
BO	5.9617000	-0.0340128
SO	5.9617000	-0.0340128

Species Code	p_0	p_1
BJ	5.9617000	-0.0340128
CK	5.9617000	-0.0340128
SW	5.9617000	-0.0340128
BR	5.9617000	-0.0340128
SN	5.9617000	-0.0340128
PO	5.9617000	-0.0340128
DO	5.9617000	-0.0340128
CO	5.9617000	-0.0340128
PN	5.9617000	-0.0340128
CB	5.9617000	-0.0340128
QI	5.9617000	-0.0340128
OV	5.9617000	-0.0340128
WK	5.9617000	-0.0340128
NK	5.9617000	-0.0340128
WL	5.9617000	-0.0340128
QS	5.9617000	-0.0340128
UH	5.9617000	-0.0340128
SS	5.1676998	-0.0077681
OB	5.1676998	-0.0077681
CA	5.9617000	-0.0340128
PS	5.9617000	-0.0340128
HL	5.9617000	-0.0340128
BP	5.9617000	-0.0340128
BT	5.9617000	-0.0340128
QA	5.9617000	-0.0340128
BK	5.1676998	-0.0077681
OL	5.1676998	-0.0077681
SY	5.9617000	-0.0340128
BY	5.5876999	-0.0053480
RB	5.9617000	-0.0340128
SU	5.9617000	-0.0340128
WI	5.1676998	-0.0077681
BL	5.1676998	-0.0077681
NC	5.9617000	-0.0340128
AH	5.1676998	-0.0077681
RD	5.1676998	-0.0077681
DW	5.1676998	-0.0077681
HT	5.9617000	-0.0340128

Species Code	p_0	p_1
KC	5.1676998	-0.0077681
OO	5.1676998	-0.0077681
CT	5.9617000	-0.0340128
MV	5.9617000	-0.0340128
MB	5.1676998	-0.0077681
HH	5.1676998	-0.0077681
SD	5.1676998	-0.0077681

When stand density-related mortality is in effect, the total amount of stand mortality is determined based on the trajectory developed from the relationship between stand SDI and the maximum SDI for the stand. This is explained in section 7.3.2.1 of EFVS.

Once the amount of stand mortality is determined based on either the summation of background mortality rates or density-related mortality rates, mortality is dispersed to individual tree records in relation to a tree's height relative to the average stand height (*RELHT*) using equation {5.0.3}. This value is then adjusted by a species-specific mortality modifier representing the species shade tolerance shown in equation {5.0.4}.

The mortality model makes multiple passes through the tree records multiplying a record's trees-per-acre value times the final mortality rate (*MORT*), accumulating the results, and reducing the trees-per-acre representation until the desired mortality level has been reached. If the stand still exceeds the basal area maximum sustainable on the site the mortality rates are proportionally adjusted to reduce the stand to the specified basal area maximum.

{5.0.3} $MR = 0.84525 – (0.01074 * RELHT) + (0.0000002 * RELHT^3)$

{5.0.4} $MORT = MR * (1 – MWT) * 0.1$

where:

MR	is the proportion of the tree record attributed to mortality (bounded: $0.01 \leq MR \leq 1$)
RELHT	is tree height divided by average height of the 40 largest diameter trees in the stand
MORT	is the final mortality rate of the tree record
MWT	is a mortality weight value shown in Table 5.0.2

Table 5.0.2 *MWT* values for the mortality equation {5.0.4} in the CS variant.

Species Code	*MWT*
RC	0.20
JU	0.70
SP	0.30
VP	0.30
LP	0.30
OS	0.30
WP	0.50

Species Code	*MWT*
SK	0.50
BO	0.50
SO	0.10
BJ	0.70
CK	0.30
SW	0.50
BR	0.50

Species Code	***MWT***
WN	0.30
BN	0.30
TL	0.30
TS	0.70
WT	0.30
BG	0.30
HS	0.50
SH	0.50
SL	0.90
MH	0.30
PH	0.50
HI	0.50
WH	0.50
BH	0.50
PE	0.50
BI	0.50
AB	0.70
BA	0.30
PA	0.50
UA	0.30
EC	0.10
RM	0.85
BE	0.70
SV	0.70
BC	0.40
AE	0.50
SG	0.50
HK	0.50
WE	0.30
EL	0.50
SI	0.50
RL	0.70
RE	0.50
YP	0.30
BW	0.70
SM	0.90
AS	0.30
WA	0.30
GA	0.70
WO	0.50

Species Code	***MWT***
SN	0.30
PO	0.30
DO	0.70
CO	0.50
PN	0.30
CB	0.30
QI	0.30
OV	0.50
WK	0.30
NK	0.90
WL	0.30
QS	0.70
UH	0.50
SS	0.30
OB	0.30
CA	0.70
PS	0.90
HL	0.70
BP	0.10
BT	0.10
QA	0.10
BK	0.10
OL	0.30
SY	0.50
BY	0.50
RB	0.30
SU	0.30
WI	0.90
BL	0.10
NC	0.30
AH	0.90
RD	0.30
DW	0.90
HT	0.30
KC	0.10
OO	0.30
CT	0.50
MV	0.50
MB	0.30
HH	0.70

Species Code	***MWT***
RO	0.50

Species Code	***MWT***
SD	0.70

6.0 Regeneration

The CS variant contains a partial establishment model which may be used to input regeneration and ingrowth into simulations. A more detailed description of how the partial establishment model works can be found in section 5.4.5 of the Essential FVS Guide (Dixon 2002).

The regeneration model is used to simulate stand establishment from bare ground, or to bring seedlings and sprouts into a simulation with existing trees. Sprouts are automatically added to the simulation following harvest or burning of known sprouting species (see table 6.0.1 for sprouting species).

Table 6.0.1 Regeneration parameters by species in the CS variant.

Species Code	Sprouting Species	Minimum Bud Width (in)	Minimum Tree Height (ft)	Maximum Tree Height (ft)
RC	No	0.5	0.33	16.0
JU	No	0.3	2.10	27.0
SP	Yes	0.5	0.25	14.0
VP	No	0.5	0.42	14.0
LP	No	0.5	0.25	14.0
OS	No	0.3	0.25	16.0
WP	No	0.4	0.33	20.0
WN	Yes	0.4	0.33	20.0
BN	Yes	0.3	0.33	18.0
TL	Yes	0.2	0.33	16.0
TS	Yes	0.2	3.59	20.0
WT	Yes	0.2	0.33	20.0
BG	Yes	0.2	0.33	16.0
HS	Yes	0.3	0.33	14.0
SH	Yes	0.3	0.33	14.0
SL	Yes	0.3	0.33	14.0
MH	Yes	0.3	0.33	18.0
PH	Yes	0.3	0.33	14.0
HI	Yes	0.3	0.33	14.0
WH	Yes	0.3	0.33	14.0
BH	Yes	0.3	0.33	14.0
PE	Yes	0.3	0.33	14.0
BI	Yes	0.3	0.33	14.0
AB	Yes	0.1	0.25	14.0
BA	Yes	0.2	0.33	18.0
PA	Yes	0.2	0.42	28.0
UA	Yes	0.2	0.50	20.0
EC	Yes	0.1	0.42	24.0

Species Code	Sprouting Species	Minimum Bud Width (in)	Minimum Tree Height (ft)	Maximum Tree Height (ft)
RM	Yes	0.2	1.00	20.0
BE	Yes	0.3	0.33	16.0
SV	Yes	0.2	0.42	18.0
BC	Yes	0.1	0.42	26.0
AE	Yes	0.1	0.33	16.0
SG	Yes	0.3	0.33	14.0
HK	Yes	0.1	0.25	12.0
WE	Yes	0.1	0.50	20.0
EL	Yes	0.1	0.33	16.0
SI	Yes	0.1	0.50	20.0
RL	Yes	0.1	0.33	12.0
RE	Yes	0.1	0.50	20.0
YP	Yes	0.2	0.42	24.0
BW	Yes	0.1	0.33	16.0
SM	Yes	0.2	0.25	16.0
AS	Yes	0.2	0.42	24.0
WA	Yes	0.2	0.42	24.0
GA	Yes	0.2	0.42	24.0
WO	Yes	0.2	0.33	16.0
RO	Yes	0.2	0.42	20.0
SK	Yes	0.1	0.33	16.0
BO	Yes	0.2	0.33	16.0
SO	Yes	0.2	0.33	16.0
BJ	Yes	0.2	2.80	20.0
CK	Yes	0.1	0.33	12.0
SW	Yes	0.1	0.33	16.0
BR	Yes	0.2	0.25	14.0
SN	Yes	0.2	0.33	12.0
PO	Yes	0.1	0.25	12.0
DO	Yes	0.1	2.80	20.0
CO	Yes	0.2	0.33	16.0
PN	Yes	0.2	1.40	20.0
CB	Yes	0.1	0.33	14.0
QI	Yes	0.2	0.25	14.0
OV	Yes	0.2	0.50	20.0
WK	Yes	0.1	0.33	16.0
NK	Yes	0.2	1.40	20.0
WL	Yes	0.1	0.25	14.0
QS	Yes	0.1	0.50	20.0
UH	No	0.2	1.40	20.0

Species Code	Sprouting Species	Minimum Bud Width (in)	Minimum Tree Height (ft)	Maximum Tree Height (ft)
SS	Yes	0.1	0.50	18.0
OB	Yes	0.1	0.55	20.0
CA	Yes	0.3	0.63	20.0
PS	Yes	0.1	0.25	12.0
HL	Yes	0.1	5.00	20.0
BP	Yes	0.2	0.42	24.0
BT	Yes	0.2	0.42	20.0
QA	Yes	0.3	0.42	20.0
BK	Yes	0.1	0.58	24.0
OL	No	0.2	1.40	20.0
SY	Yes	0.1	0.58	24.0
BY	Yes	0.2	1.40	20.0
RB	Yes	0.1	0.33	18.0
SU	Yes	0.2	0.33	18.0
WI	Yes	0.1	4.70	20.0
BL	Yes	0.1	1.00	32.0
NC	No	0.1	0.33	10.0
AH	Yes	0.2	0.42	20.0
RD	Yes	0.2	2.10	20.0
DW	Yes	0.1	0.25	18.0
HT	Yes	0.1	0.25	16.0
KC	Yes	0.1	0.50	20.0
OO	Yes	0.2	0.25	12.0
CT	Yes	0.2	0.33	20.0
MV	Yes	0.2	0.42	20.0
MB	Yes	0.2	2.10	20.0
HH	Yes	0.2	0.42	20.0
SD	Yes	0.2	0.33	16.0

The number of sprout records created for each sprouting species is found in table 6.0.2. For more prolific stump sprouting hardwood species, logic rule {6.0.1} is used to determine the number of sprout records, with logic rule {6.0.2} being used for root suckering species. The trees-per-acre represented by each sprout record is determined using the general sprouting probability equation {6.0.3}. See table 6.0.2 for species-specific sprouting probabilities, number of sprout records created, and reference information.

Users wanting to modify or turn off automatic sprouting can do so with the SPROUT or NOSPROUT keywords, respectively. Sprouts are not subject to maximum and minimum tree heights found in table 6.0.1 and do not need to be grown to the end of the cycle because estimated heights and diameters are end of cycle values.

{6.0.1} For stump sprouting hardwood species

$DSTMP_i \le 5$: $NUMSPRC = 1$
$5 < DSTMP_i \le 10$: $NUMSPRC = \mathrm{NINT}(0.2 * DSTMP_i)$
$DSTMP_i > 10$: $NUMSPRC = 2$

{6.0.2} For root suckering hardwood species

$DSTMP_i \le 5$: $NUMSPRC = 1$
$5 < DSTMP_i \le 10$: $NUMSPRC = \mathrm{NINT}(-1.0 + 0.4 * DSTMP_i)$
$DSTMP_i > 10$: $NUMSPRC = 3$

{6.0.3} $TPA_s = TPA_i * PS$

{6.0.4} $PS = (1.6134 - 0.0184 * (((DSTMP_i / 0.7788 - 0.21525) * 2.54)))/(1 + \exp(1.6134 - 0.0184 * (((DSTMP_i / 0.7788) - 0.21525) * 2.54)))$

{6.0.5} $PS = (6.0065 - 0.0777*((DSTMP_i / 0.7801) * 2.54)) / (1 + \exp(6.0065 - 0.0777 * ((DSTMP_i / 0.7801) * 2.54)))$

{6.0.6} $PS = (6.4205 - 0.1097 * (((DSTMP_i / 0.8188 - 0.23065) * 2.54))) / (1 + \exp(6.4205 - 0.1097 * (((DSTMP_i / 0.8188) - 0.23065) * 2.54)))$

{6.0.7} $PS = ((57.3 - 0.0032 * (DSTMP_i)^3) / 100)$

{6.0.8} $PS = (1 / (1 + \exp(-(2.3656 - 0.2781 * (DSTMP_i / 0.7801)))))$

{6.0.9} $PS = (1 / (1 + \exp(-(-2.8058 + 22.6839 * (1 / ((DSTMP_i / 0.7788) - 0.4403))))))$

{6.0.10} $PS = (TPA_i / (ASTPAR * 2)) * ((ASBAR / 198) * (40100.45 - 3574.02 * RSHAG^2 + 554.02 * RSHAG^3 - 3.5208 * RSHAG^5 + 0.011797 * RSHAG^7))$

{6.0.11} $PS = ((89.191 - 2.611 * DSTMP_i) / 100)$

where:

$DSTMP_i$	is the diameter at breast height of the parent tree
$NUMSPRC$	is the number of sprout tree records
NINT	rounds the value to the nearest integer
TPA_s	is the trees per acre represented by each sprout record
TPA_i	is the trees per acre removed/killed represented by the parent tree
PS	is a sprouting probability (see Table 6.0.2)
$ASBAR$	is the aspen basal area removed
$ASTPAR$	is the aspen trees per acre removed
$RSHAG$	is the age of the sprouts at the end of the cycle in which they were created

Table 6.0.2 Sprouting algorithm parameters for sprouting species in the CS variant.

Species Code	Sprouting Probability	Number of Sprout Records	Source*
SP	0.42 for DBH < 7”, 0 for DBH > 7”	1, 0	Wayne Clatterbuck (personal communication) Ag. Handbook 654
WN	0.8 for DBH < 8",	1	Schlesinger 1977

Species Code	Sprouting Probability	Number of Sprout Records	Source*
	0.5 for DBH > 8"		Schlesinger 1989 Coladonato 1991
BN	0.3 for DBH < 8", 0 for DBH > 8"	1, 0	Ag. Handbook 654
TL	0.9	1	Ag. Handbook 654
TS	0.9	1	Hook and DeBell 1970 Ag. Handbook 654
WT	0.9	1	Hook and DeBell 1970 Ag. Handbook 654
BG	0.9	1	Hook and DeBell 1970 Ag. Handbook 654
HS	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Ag. Handbook 654
SH	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Nelson 1965
SL	0.75 for DBH < 24", 0.5 for DBH > 24"	1	Ag. Handbook 654
MH	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Nelson 1965
PH	0.75 for DBH < 24", 0.5 for DBH > 24"	1	Ag. Handbook 654
HI	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Ag. Handbook 654
WH	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Ag. Handbook 654
BH	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Nelson 1965 Fayle 1966
PE	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Wolstenholme 1976 Ag. Handbook 654
BI	0.95 for DBH < 24", 0.6 for DBH > 24"	1	Nelson 1965 Ag. Handbook 654
AB	0.5 for DBH < 4", 0 for DBH > 4"	1, 0	Ag. Handbook 654
BA	0.8 for DBH < 12", 0.5 for DBH > 12"	{6.0.1}	Curtis 1959 Lees and West 1988
PA	0.8 for DBH < 12", 0.5 for DBH > 12"	{6.0.1}	Ag. Handbook 654
UA	0.8 for DBH < 12", 0.5 for DBH > 12"	{6.0.1}	Ag. Handbook 654
EC	0.4 for DBH < 25", 0 for DBH > 25"	1, 0	Ag. Handbook 654

Species Code	Sprouting Probability	Number of Sprout Records	Source*
RM	0.8 for DBH < 12", 0.5 for DBH > 12"	{6.0.1}	Solomon and Barton 1967 Prager and Goldsmith 1977
BE	0.6 for DBH < 15", 0.3 for DBH > 15"	1	Maeglin and Ohman 1973 Eyre 1980
SV	0.8 for DBH < 12", 0.5 for DBH > 12"	{6.0.1}	Ag. Handbook 654
BC	0.8 for DBH < 12", 0.5 for DBH > 12"	1	Hough 1965 Powell and Tryon 1979
AE	0.7	1	Ag. Handbook 654
SG	0.8	1	Ag. Handbook 654
HK	0.4 for DBH < 8", 0.2 for DBH > 8"	1	Ag. Handbook 654
WE	0.7	1	Ag. Handbook 654
EL	0.7	1	Ag. Handbook 654
SI	0.7	1	Ag. Handbook 654
RL	0.7	1	Ag. Handbook 654
RE	0.7	1	Ag. Handbook 654
YP	0.8 for DBH < 25", 0.5 for DBH > 25"	{6.0.2}	Ag. Handbook 654
BW	0.8	{6.0.2}	Ag. Handbook 654
SM	{6.0.11}	{6.0.1}	MacDonald and Powell 1983 Ag. Handbook 654
AS	0.8 for DBH < 12", 0.5 for DBH > 12"	1	Ag. Handbook 654
WA	0.8 for DBH < 12", 0.5 for DBH > 12"	1	Ag. Handbook 654
GA	0.8 for DBH < 12", 0.5 for DBH > 12"	1	Ag. Handbook 654
WO	Eq. {6.0.4}	1	Sands and Abrams 2009 Westfall 2010 Ag. Handbook 654
RO	Eq. {6.0.7}	{6.0.1}	Johnson 1975 Ag. Handbook 654
SK	0.8 for DBH < 10", 0.5 for DBH > 10"	1	Ag. Handbook 654
BO	Eq. {6.0.5}	1	Sands and Abrams 2009 Westfall 2010 Ag. Handbook 654
SO	Eq. {6.0.7}	1	Johnson 1975 Ag. Handbook 654
BJ	Eq. {6.0.8}	1	Johnson 1977

Species Code	Sprouting Probability	Number of Sprout Records	Source*
			Ag. Handbook 654
CK	0.7	1	Ag. Handbook 654
SW	90% of Eq. {6.0.4} predictions	1	Ag. Handbook 654
BR	0.8	1	Ag. Handbook 654
SN	Eq. {6.0.6}	1	Sands and Abrams 2009 Westfall 2010 Ag. Handbook 654
PO	Eq. {6.0.9}	1	Johnson 1977 Ag. Handbook 654
DO	Eq. {6.0.9}	1	Johnson 1977 Ag. Handbook 654
CO	Eq. {6.0.6}	1	Sands and Abrams 2009 Westfall 2010 Ag. Handbook 654
PN	0.8	1	Ag. Handbook 654
CB	Eq. {6.0.7}	{6.0.1}	Johnson 1975 Ag. Handbook 654
QI	Eq. {6.0.7}	{6.0.1}	Johnson 1975 Ag. Handbook 654
OV	0.4 for DBH < 8", 0 for DBH > 8"	1, 0	Ag. Handbook 654
WK	0.7	1	Carey 1992-1
NK	0.8 for DBH < 10", 0.5 for DBH > 10"	1	Ag. Handbook 654
WL	0.8 for DBH < 10", 0.5 for DBH > 10"	1	Ag. Handbook 654
QS	0.6 for DBH < 10", 0.3 for DBH > 10"	1	Ag. Handbook 654
SS	0.8	{6.0.2}	Ag. Handbook 654
OB	0.4 for DBH < 8", 0 for DBH > 8"	1, 0	Ag. Handbook 654
CA	No info available—default to 0.7	1	n/a
PS	0.7	1	Ag. Handbook 654
HL	0.7	1	Ag. Handbook 654
BP	0.8 for DBH < 25", 0.5 for DBH > 25"	{6.0.2}	Ag. Handbook 654
BT	0.8	{6.0.2}	Ag. Handbook 654
QA	Eq. {6.0.10}	2	Keyser 2001
BK	0.9	{6.0.1}	Ag. Handbook 654

Species Code	Sprouting Probability	Number of Sprout Records	Source*
SY	0.7	1	Steinbeck et al. 1972 Sullivan 1994
BY	0.8 for DBH < 12", 0.5 for DBH > 12"	1	Ag. Handbook 654
RB	0.7	1	Sullivan 1993
SU	0.7	1	Coladonato 1992-1 Ag. Handbook 654
WI	0.9	1	Ag. Handbook 654
BL	0.9	1	Ag. Handbook 654
AH	No info available—default to 0.7	1	n/a
RD	0.8	1	Armstrong 1980
DW	0.7 for DBH < 8", 0.9 for DBH > 8"	{6.0.1}	Ag. Handbook 654
HT	No info available—default to 0.7	1	n/a
KC	No info available—default to 0.7	1	n/a
OO	0.8	1	Carey 1994-1
CT	0.7	1	Ag. Handbook 654
MV	0.8	{6.0.2}	Jones et al. 2000
MB	0.8	1	Ag. Handbook 654
HH	0.8	1	Ag. Handbook 654
SD	0.9	{6.0.1}	Ag. Handbook 654

*Many of the sources stemmed from those referenced in Agricultural Handbook 654, Silvics of North America. For the sake of being concise, only “Ag. Handbook 654” was listed when multiple publications were referenced from that handbook. When necessary, species-specific probabilities were based upon similarities with other species, either due to documented similarities or an assumed similarity. In the latter cases, assumptions were necessary due to a lack of previous research findings for these species.

Regeneration of seedlings must be specified by the user with the partial establishment model by using the PLANT or NATURAL keywords. Height of the seedlings is estimated in two steps. First, the height is estimated when a tree is 5 years old (or the end of the cycle – whichever comes first) by using the small-tree height growth equations found in section 4.6.1. Users may override this value by entering a height in field 6 of the PLANT or NATURAL keyword; however the height entered in field 6 is not subject to minimum height restrictions and seedlings as small as 0.05 feet may be established. The second step also uses the equations in section 4.6.1, which grow the trees in height from the point five years after establishment to the end of the cycle.

Seedlings and sprouts are passed to the main FVS model at the end of the growth cycle in which regeneration is established. Unless noted above, seedlings being passed are subject to minimum and maximum height constraints and a minimum budwidth constraint shown in table 6.0.1. After seedling height is estimated, diameter growth is estimated using equations described in section 4.6.2. Crown ratios on newly established trees are estimated as described in section 4.3.1.

Regenerated trees and sprouts can be identified in the treelist output file with tree identification numbers beginning with the letters “ES”.

7.0 Volume

Volume is calculated for three merchantability standards: merchantable stem (pulpwood) cubic feet, sawlog stem cubic feet, and sawlog stem board feet (International ¼-inch). Volume estimation is based on methods contained in the National Volume Estimator Library maintained by the Forest Products Measurements group in the Forest Management Service Center (Volume Estimator Library Equations 2009). The default merchantability standards for the CS variant are shown in table 7.0.1.

Table 7.0.1 Volume merchantability standards for the CS variant.

Pulpwood Volume Specifications:		
Minimum DBH / Top Diameter	Hardwoods	Softwoods
905 – Mark Twain	5.0 / 4.0 inches	5.0 / 4.0 inches
908 – Shawnee	6.0 / 5.0 inches	5.0 / 4.0 inches
911 – Wayne-Hoosier, 912 - Hoosier	6.0 / 4.0 inches	5.0 / 4.0 inches
Stump Height	0.5 feet	0.5 feet
Sawtimber Volume Specifications:		
Minimum DBH / Top Diameter	Hardwoods	Softwoods
905 – Mark Twain (eastern redcedar)		6.0 / 5.0 inches
905 – Mark Twain (all other species)	9.0 / 7.6 inches	9.0 / 7.6 inches
908 – Shawnee	11.0 / 9.6 inches	9.0 / 7.6 inches
911 – Wayne-Hoosier, 912 - Hoosier	11.0 / 9.6 inches	9.0 / 7.6 inches
Stump Height	1.0 foot	1.0 foot

For both cubic and board foot prediction, Clark's profile models (Clark et al. 1991) are used for all species and all location codes in the CS variant. Equation number is 900CLKE***, where *** signifies the three-digit FIA species code.

8.0 Fire and Fuels Extension (FFE-FVS)

The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003) integrates FVS with models of fire behavior, fire effects, and fuel and snag dynamics. This allows users to simulate various management scenarios and compare their effect on potential fire hazard, surface fuel loading, snag levels, and stored carbon over time. Users can also simulate prescribed burns and wildfires and get estimates of the associated fire effects such as tree mortality, fuel consumption, and smoke production, as well as see their effect on future stand characteristics. FFE-FVS, like FVS, is run on individual stands, but it can be used to provide estimates of stand characteristics such as canopy base height and canopy bulk density when needed for landscape-level fire models.

For more information on FFE-FVS and how it is calibrated for the CS variant, refer to the updated FFE-FVS model documentation (Rebain, comp. 2010) available on the FVS website.

9.0 Insect and Disease Extensions

FVS Insect and Disease models have been developed through the participation and contribution of various organizations led by Forest Health Protection. The models are maintained by the Forest Health Technology Enterprise Team (FHTET) and regional Forest Health Protection specialists. There are no insect and disease models currently available for the CS variant. However, FVS addfiles that simulate the effects of known agents within the CS variant may be found at the FHTET website.

10.0 Literature Cited

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11.0 Appendices

There are no appendices for the CS variant.