AN ABSTRACT OF THE DISSERTATION OF

Michael R. Vanderberg for the degree of Doctor of Philosophy in Forest Engineering presented on April 14, 2011.

Title: The Role of Strategic Planning in the Management of Fire-prone Western Oregon Forests for Maximizing Terrestrial Carbon Stocks over a100-year Horizon

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Current frameworks for analyzing forest carbon offset projects in disturbance-prone western forests often fail to address the dynamic nature of carbon pathways through time. They do not account for the probability of loss due to wildfire, which can influence the prediction of carbon storage at the end of a planning horizon. In such an environment, optimal treatment regimes over time are dependent on the decisions that affect carbon storage during the analysis period. Silvicultural regimes that include both pyrogenic and biogenic emissions from forests, as well as the storage in wood products, were modeled to demonstrate a method to maximize carbon storage.

Stand-level optimization is suggested as a method for demonstrating the development of treatment regimes to enable a full range of carbon storage benefits. These include a reduction in the risk of catastrophic wildfire, increased terrestrial carbon density, and the offset of treatment costs. This methodology may also provide a baseline for a full accounting of forestry carbon offset projects.

A model was developed to determine optimal management regimes that maximize the expected value of terrestrial carbon storage for three Douglas-fir *(Pseudotsuga menziessi)* dominant forests in western Oregon. Carbon storage values for treatment combinations were weighted by the probability of fire occurrence and the loss of carbon due to fire. The model employs probabilistic dynamic programming to determine the optimal timing and intensity of silvicultural treatments by way of thinning-from-below. Also determined are location-dependent management regimes that maximize aboveground carbon storage with fire-suppression efforts. The stand location in respect to roads is examined, specifically in terms of the effect that access distance and slope position have on the optimal timing and intensity of fuel treatments and silvicultural activities. Optimal regimes are determined for a range of forest stands, varying by stand distance-to-road and the slope location of the road above or below the stand.

Results suggest that a combination of let-grow and low-level density-reduction thinnings can store more aboveground terrestrial carbon in forests and long-lived wood products than grow-only control scenarios when fire is also present and fire-related emissions are accounted for. Additional expected carbon storage of optimal solutions compared to the 100-year gain for control scenarios ranged from 0 to 46%. This suggests that strategic planning by the optimization model can compete with the hedge method of the Voluntary Carbon Standard risk management, which employs carbon buffer pools to compensate for the risk associated with disturbance and can require the size of the buffer deposit to range from 10 to 60% of the generated carbon credits, depending on the risk class determined for a given project.

Results also suggest that both stand location and fire suppression efforts did not impact the maximization of aboveground terrestrial carbon storage in forests and long-lived wood products under moderate fire conditions (21 km hr^{-1} 6-meter wind speed, 31° C air temperature, 40% herbaceous and 70% woody fuel moisture). However, it was shown that stand slope position relative to access roads did impact fire suppression efforts by affecting the response time and the type of suppression effort (e.g., head attack or rear attack). It is hypothesized that both stand location and fire suppression efforts would impact the maximization of aboveground terrestrial carbon in forests and wood products under more severe weather conditions, on steeper slopes, and over larger stand areas.

The Role of Strategic Planning in the Management of Fire-prone Western Oregon Forests for Maximizing Terrestrial Carbon Stocks over a 100-year Horizon

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Michael R. Vanderberg, Author

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CHAPTER 1

GENERAL

INTRODUCTION

1.1 INTRODUCTION

1.1.1 Literature Review

Many forest management practices in the western United States, coupled with wildfire suppression, have resulted in an increased risk of high-intensity wildfires, especially in dry western forests (Keegan et al. 2004, Schoennagel et al. 2004, Little 2003, O'Laughlin and Cook 2003, Waltz et al. 2003, Chase 2001, Fule et al. 2001). New policies on many of these lands have subsequently failed to counteract the accumulation of fuels in western forests, and have allowed for the tree density of some forest sites to increase by a magnitude of eight times over the past 100 years (Busenberg 2004). The forests of the Pacific Northwest (PNW), notably those fire-prone forests of western Oregon, are no exception (Westerling et al. 2006, Dombeck et al. 2004), and many of the communities located on the wildland-urban interface (WUI) have been threatened by the potential increase in wildfire risk (Berry and Hesseln 2004, Brunson and Schindler 2004, Winter et al. 2002).

Another area of concern is the increase in atmospheric carbon dioxide (CO_2), which may be at least partially caused by anthropogenic emissions (Apps and Price 1996). There is a significant amount of literature surrounding the role that forests may play in sequestering carbon, thus decreasing, or at least slowing the net emission of CO_2 to the atmosphere. However, while the overstocked western forests are accumulating and storing carbon, the same forests are simultaneously becoming a large potential source of carbon emission to the atmosphere as the probability of wildfire increases. The current method of risk reduction is forest fuels silvicultural treatments (i.e., hazardous fuels reduction – HFR), which mostly involves the removal of smaller-diameter trees to reduce stocking levels. This method has led to the emergence of several locally-centered wood utilization facilities that use innovative techniques to produce products from smaller diameter timber, while creating employment for the communities involved (Levan-Green and Livingston 2001). There are also biomass utilization facilities that have evolved from the need to generate revenue through the utilization of the residuals from some HFR activities, such as near the Lassen and Shasta-Trinity National Forests in northern California (Bergman and Zerbe 2004). The combination of HFR projects, biomass utilization for energy production, and smallwood utilization for solidwood products facilities can result in substantial benefits, such as reduced fire fighting costs, habitat and timber losses, and atmospheric carbon emission; as well as economic benefits (Mason et al. 2006).

The idea of storing carbon in as harvested wood products (HWPs) has been widely recognized by scientists throughout the past decade (Kohlmaier et al. 2007, Arroja et al. 2006, Pingoud and Wagner 2006, Backéus et al. 2005, Dias et al. 2005, Lippke et al. 2004, Masera et al. 2003, Brown 2002, Hashimoto et al. 2002, Pingoud and Lehtilä 2002, Liski et al. 2001, Pingoud et al. 2001, Karjalainen et al. 1999, Lim et al. 1999, Harmon et al. 1996, Heath et al. 1996). Still, some researchers suggest that HWPs deserve considerably more attention (Pingoud et al. 2004, Richards and Stokes 2004, Niles and Schwarze 2001), and meanwhile, some forest carbon sequestration (i.e., forest carbon flux) studies fail to include HWPs as part of their calculations (Sohngen and Mendelsohn 2003, Casperson et al. 2000). Also, it seems that most research conducted on HWPs as carbon stores are macro-level studies aimed at estimating the contribution at a global or national scale, which can have unacceptable levels of uncertainty when evaluating project level decisions (Skog et al. 2004, Nabuurs and Sikkema 2001, Phillips et al. 2000). Harmon (2001) recommends examining carbon sequestration projects at several scales, theorizing that findings at one scale do not necessarily directly translate to a scale of different resolution or magnitude.

1.1.2 Forest Fuels – Current Status

Some researchers have concluded that over two-thirds of 81 million hectares of federally managed forestlands are in severely degraded conditions in terms of fuel load (Fule et al. 2001). Others have calculated that a figure of 77 million hectares of public land is currently at an increased risk of catastrophic wildfire (Schoennagel et al. 2004). Researchers have also noted that in some western states, such as Montana, that 80-percent of the forests within the state rate as high or moderate in regards to potential fire hazard (Keegan et al. 2004). In the state of Arizona, some forests are experiencing tree densities that are, on average, twenty times the historical density, and basal areas that are four to six times higher (Waltz et al. 2003). In Colorado, some ponderosa pine (Pinus ponderosa) forests exhibit a stocking level of up to 964 trees per hectare, with an average diameter of 20 cm (Little 2003). Other factors also arise from the increased tree density of the U.S. National Forests. O'Laughlin and Cook (2003) mention that National Forests contain more biomass per acre than other forestlands, which could potentially lead towards a higher risk of insect infestation and other forest pathogens, increased rates of tree mortality, and increased wildfire. In summary, many western forests are in condition in which they are outside the historic range of variability due to a large number of contributing factors (Waltz et al. 2003, Fule et al. 2001, Fule and Covington 1998).

In response to the recent increase in high-intensity wildfires that have occurred across the western U.S. in the recent years, there has also been an increased interest in reducing the fuel load found in some forestlands. Fire has an important history in the forests of the western U.S., from infrequent, high-severity, stand replacing fires in high-elevation subalpine forests to frequent low-severity "cleaning" fires in ponderosa pine forests (Schoennagel et al. 2004). The effects of decades of fire suppression and high-grade harvesting activity (removing only the largest and most valuable trees) has caused intermediate and understory trees to accumulate and increase in density, providing "ladder fuels" that allow wildfires to reach the canopy of the overstory trees (Nakamura 2004, Schoennagel et al. 2004). Nakamura (2004) states that ladder fuels can be considered trees that are 5 to 25 cm in diameter at breast height (DBH) and 3 to 12 meters in height. Nakamura (2004) also notes that the larger ladder fuels (15 to 25 cm DBH) can represent competition for limited soil moisture, and can cause undue stress on the overstory trees.

In order to reduce the overload of forest fuels in many of the western forest ecosystems, prescribed burns were introduced. Prescribed burning is may be limited in current forests due high fuel loadings. Also, mechanical forest fuels reduction is another option for controlling the overstocked western forests and reducing the risk of catastrophic wildfire.

1.1.3 Treatment Overview

1.1.3.1 *Prescribed Fire*

Fire is nature's way of reducing fuel loads and maintaining a relatively open forest structure. Prescribed fire, defined by Yoder and Blatner (2004), is fire intentionally started for a specific, predetermined land management goal, whether or not the fire ultimately extends beyond its prescription. The general land management goal is reducing fuel loads and restoring forestlands to their previous state. Potentially, the most important aspect of introducing prescribed fire to a forested area is the temporal framework of treatment. The timing of fire treatments is important because fire risk changes as the vegetation changes and matures. For example, on a year-by-year basis, if the perceived benefits of prescribed fire are greater than the potential damage of waiting an additional year, a prescribed fire treatment should be implemented (Yoder and Blatner 2004).

The long-term goal of prescribed fire treatments is that through initial and potentially necessary subsequent treatments the forestland will eventually reach a state similar to pre-European settlement conditions, in which the forested area can then maintain fuel loads through natural fire intervals (Brown et al. 1999). Many forests have experienced fire suppression for too long a time or have unusually high fuel loads for other reasons (as is the case for many western forestlands), and prescribed burns can be unsafe treatments resulting in uncontrollable and catastrophic high-intensity crown fires, or severe surface fires that may cause crown, root, or cambium injury that could lead to substantial tree mortality, even without spreading to the crown canopy (Yoder and Blatner 2004, Keyes and O'Hara 2002). Another drawback of prescribed fire is the un-predictive nature of fire itself, which may lead to unexpected implications (e.g., the escape of fire from within its intended boundaries). In the year 2000, a prescribed fire blew out of control, burning over 19,000 hectares and destroying more than 200 homes in New Mexico (Brunson and Shindler 2004).

The social acceptance of prescribed fire treatments for HFR and restoration efforts are widely accepted across Eastern Oregon (Brunson and Shindler 2004, Shindler and Toman 2003). However, Shindler and Toman (2003) showed that there is growing public concern over the use of prescribed fire, as their survey showed a 15-percent increase, between the years 1996 and 2000, in participants who view smoke pollution as a potential problem. The same study showed a five-percent decrease in participants who view prescribed fire as a legitimate tool to use anywhere. The increase in public concern could be partially attributed to the residential growth at the WUI (Winter et al. 2002), and the shortage of academic-related public extension (Shindler and Toman 2003).

1.1.3.2 *Mechanical Treatments*

Mechanical hazardous fuels reduction, (i.e., forest restoration treatments) typically remove trees that are 20 cm and smaller, although other diameter limitations could apply depending on the current conditions of each site (Fight et al. 2004). Mechanical fuels reduction utilizes mechanized equipment to harvest or masticate ladder fuels and understory vegetation to inhibit wildfire from reaching the upper tree crown canopy, while restoring the forest to a structure similar to its pre-European settlement condition. Harvested smallwood can be removed from the forest and could have potential market value, while masticated woody debris is usually spread out on the forest floor or removed and burned. Mechanical fuel reduction treatments are immediately effective, and are not hampered by the troubles associated with prescribed burns, such as air pollution from smoke particulates or escaping fires (Hollenstein et al. 2001). Mechanical treatments, however, can cause repeated soil disturbance, which may have an impact on the sustainability of soils and site productivity (Fule and Covington 1998).

There is no shortage of support for mechanical fuels reduction. O'Laughlin and Cook (2003) agree that National Forest land conditions could be improved through fuel reduction treatments that target insect and disease prone trees. Fule et al. (2001) showed that stands that were left untreated had a 48-percent increase canopy fire, higher flame lengths, heat per area, and rate of fire spread than stands that had undergone fuel reduction treatments. It was also stated that the restoration treatments clearly made an enhancement in the resistance to crown fire. Mechanical fuel reduction treatments are recommended for low-severity fire regimes in low-elevation ponderosa pine forests and mixed-severity fire regimes in the Rocky Mountain region. However, mechanical treatments are not recommended for initially reducing fuel loads in high-severity fire regimes of subalpine forests (Schoennagel et al. 2004).

Some mechanical fuels reduction treatments have gained broad local support. In a study conducted by Brunson and Shindler (2004), 64-percent of Oregon residents surveyed thought that mechanical fuels reduction is a legitimate tool to use anywhere.

61-percent and 58-percent of Arizona and Colorado residents surveyed, respectively, thought likewise. Responses for prescribed fire as a legitimate tool to use anywhere were an average of 10-precent lower. In the same study, 85-percent of Oregon residents surveyed thought that mechanical vegetation removal was an effective tool for reducing the frequency of wildfires. 73-percent, 74-percent, and 61-percent of Arizona, Colorado, and Utah residents surveyed, respectively, thought the same. Shindler and Toman (2003) show that public support for mechanical fuel reduction treatments in Eastern Oregon remained steady over a four-year period, actually increasing from 68-percent in 1996 to 69-percent in 2000.

There is also support for mechanical fuel reduction treatments at the (WUI). Winter et al. (2002) showed that mechanical methods are preferred close to developed areas, especially when community stakeholders were included in the planning procedure and mitigation measures were taken to reduce the aesthetic impacts and the cost-effectiveness of the program was compared to other strategies. Berry and Hesseln (2004) showed that the per acre costs of fuel reduction treatments are higher at the WUI for both mechanical and prescribed burned treatments.

1.1.3.3 *Combined Treatments*

Brockway et al. (2002) offer one other alternative, used as an example for restoring natural grassland areas from juniper forestlands. After treating the forest overstory by mechanical methods, the authors followed the mechanical treatment with prescribed fire. The authors found that this methodology resulted in an increase in plant species richness and diversity, understory biomass, and litter cover.

Additionally, the authors found no change in soil chemistry or plant nutrient status. As a purely forest restoration effort the use of both prescribed fire and mechanical removal may be the correct choice in achieving management goals in certain situations. However, as for reducing fuel loads, especially ladder fuels, an increase in understory biomass would not appear to be beneficial in accomplishing treatment goals.

1.1.4 Smallwood Harvesting Overview

The harvesting practices associated with the smallwood constraints of forest fuels reduction are varied and are many times determined based on stand and site characteristics, or silvicultural objectives; and whether or not the activity is harvesting for solidwood products, biomass, or utilizing both as residuals. Harvesting for fuels reduction purposes is many times not viewed as an economic opportunity, yet under the right circumstances, activities could yield a profit.

Smallwood can be utilized while producing long-lived solidwood products (SWPs), such as dimension and nondimension softwood lumber, engineered wood products (EWPs), glue-laminated timbers (GLULAM), and structural roundwood (Levan-Green and Livingston 2001). Long-lived SWPs can serve as carbon stores for the life of the product or longer, whereas burning HFR residuals emits carbon to the atmosphere without creating gross revenue. The use of biomass as bioenergy can reduce the current state of fossil fuels utilization, which may also help mitigate global climate change (Cuiping et al. 2004, Nakamura 2004, Bjorheden et al. 2003, Kumar et al. 2003, Malkki and Virtanen 2003). Energy produced from biomass, or bioenergy, is a potentially attractive form of energy due to it being a renewable and potentially "cleaner" fuel in terms of life-cycle GHG emissions. The United States Department of Energy reported that producing 1.1 billion Mg of biomass annually, with some biomass potentially coming from HFR activities, could cut U.S. GHG emissions by 10-percent and have the potential to improve rural economies (Perlack et al. 2005).

Harvesting forest fuels specifically as biomass for energy production is mostly viewed as a commercial venture, and necessitates the generation of positive net revenues. The fusion of HFR with utilization of treatment residuals to innovative solidwood products and biomass energy production could be an important step in both protecting forests from catastrophic wildfire as well as storing carbon in long-lasting wood products and providing an alternative energy source to mitigate the effects of GHG emissions. Concurrently, any gross revenue generated from SWPs, bioenergy, or a carbon offset value associated with either can aid in defraying HFR activities. The economic feasibility of smallwood harvesting operations is an integral part of making HFR activities a reality in many at-risk forestlands.

1.1.4.1 *Economic Feasibility*

Fiedler et al. (1999) studied both cable yarding and ground-based harvesting systems for forest restoration treatments. Whether or not this study utilized a chipper was not stated. In mature stands, favoring larger trees, the ground-based system outperformed the cable yarding system, although both showed positive net revenues. When thinning from below, the ground-based system showed slight positive net revenue, while the cable yarding system failed to create a profit. In second growth stands, the ground based-system performed better than the yarding system, and managed to yield a slight profit in the stand with a density of 914 trees per hectare. Included in the recommendations of this study was to: (1) identify the stand in most need of treatment, (2) refrain from using recovered timber volumes as a driver for restoration treatments, and (3) identify trees usable as products to generate revenue that may aid in supporting the restoration treatment.

Larson and Mirth (2004) presented a case study on the economics of thinning one 85-acre ponderosa pine stand in the WUI interface of Arizona. All restoration harvesting was done manually, and tree size was limited to trees smaller than 41 cm DBH. Only logs were merchandized, with limbs and tops being piled for burning. This scenario yielded a loss of $95.43 per ha, due to a fluctuation in one of the market prices. If the market prices would have been held constant, a profit of $83.03 per ha would have been expected, again supporting the realization that small-wood harvesting for fuels reduction purposes has the potential to generate revenue.

Han et al. (2004) constructed a case study model of mechanical whole-tree harvesting system consisting of a feller-buncher, grapple skidder, processor and loader, and a chain-flail delimbing/debarking chipper (DDC). Four product cases were studied: (1) sawlog only, (2) sawlog and clean chip, (3) sawlog and biomass fuel, and (4) sawlog, biomass fuel, and clean chip. Positive net returns were gained through the sawlog only option, but all other option showed negative net returns. Four major factors affecting the economic feasibility were concluded to be: (1) forest harvesting systems must be selected carefully to suit conditions, (2) road accessibility that may limit chip vans, (3) hauling distance to manufacturing facilities must be kept as low as possible with a low-value product, and (4) increases in market prices of thinning materials will make small-diameter harvesting more feasible.

McIver et al. (2003) studied both forwarding and cable yarding harvesting systems in a fuel reduction setting. A single-grip harvester was utilized for felling and processing, and most logs that were extracted were chipped and hauled in chip-vans. The stem density was reduced by 61.6-percent in the forwarded units, and by 66.5-percent in the yarded units. The forwarded units experienced a net profit of $24 per Mg, while the yarded units experienced a net loss of $12 per Mg.

A study on the feasibility of mechanical forest fuels reduction in Montana showed promising results in terms of net revenues (Keegan et al. 2004). In this study, the economic implications of reducing forest fuels by specific silvicultural prescriptions were modeled using a "1-percent" scenario, in which only 1-percent of the high or moderate fire hazard forests would be treated each year for a 30-year period. The total volume of timber harvested due to fuels reduction would total 821 thousand cubic meters (Mm^3) of pulpwood and 300 million board feet (MMBF) of sawlogs per year. Expected net revenue generated through the treatment would average $1541 per hectare, with some stands costing more than $2471 per hectare to treat, while others yielding more than $4942 per hectare. This study also noted that the impacts of the scenario could generate up to 3000 forest product industry jobs and more than $90-million in labor income.

As with any harvesting system, forest fuels reduction and biomass harvesting for energy production have many associated costs. The economic feasibility of operations can be highly dependent on transportation distance, the availability of markets, and the current market prices of harvested material. These factors must be considered as key components towards generating positive net revenue, as small fluctuations in any of these factors could lead to economic infeasibility.

1.1.5 Synopsis

Forest fuels reduction is becoming an increasingly important topic in the fields of forest engineering, forest management, forest science, and forest social science. The recent increase in catastrophic wildfire has led to the increased need for developing new ways of dealing with wildfire and the destruction that it causes. Forest fuels reduction is one way of reducing the intensity of wildfire, and has been met with surprising public approval in the western states.

A present drawback to forest fuels reduction as a tool to restore forests to their natural states is the low value of the wood fiber compared to the high cost of removal. Although it has been shown that fuels reduction treatments can be economically feasible (Keegan et al. 2004, Larson and Mirth 2004, McIver et al. 2003, Fiedler et al. 1999), there remains a substantial lack of existing markets for fuel reduction to be carried out on the necessary scale while remaining profitable.

The economic costs of catastrophic wildfire are extremely high, and the suppression of high-intensity fire can cost anywhere from $781 per hectare to $3096 per hectare (Lynch 2004). The potential remains for the cost of fuel reduction treatment to be offset by the savings generated from the absence of the suppression of high-intensity wildfires. As forests are transformed from their present state of high-fuel load to a state similar to their pre-European settlement condition, the potential for catastrophic wildfires could be reduced. Naturally occurring, low-intensity wildfires will still be a presence, and may need to be suppressed at the WUI. The costs associated with suppressing low-intensity wildfires, however, has been shown to be as low as $30.89 per hectare (Lynch 2004), making fuels reduction treatments (and the shift towards low-intensity wildfire regimes) more appealing when compared to suppressing high-intensity wildfires.

Prescribed fire should probably not be used in all situations. In denser stands, introducing fire could lead to high-intensity crown fires that may be difficult to suppress or control, and could lead to catastrophic events at the WUI. Furthermore, if the forestland is in an isolated location and far from the WUI, a high-intensity crown fire could lead to 100-percent mortality and the replacement of the entire stand (Miller and Tausch 2002, Brown et al. 1999) even if conditions are considered safe. Prescribed fire may be better left to use as a tool to reduce fuel loads in lower-density forests, where the risk of high-intensity catastrophic fire is low, and the perceived success of suppression efforts is high.

Although both prescribed fire and mechanical treatments can both be used to effectively reduce fuel loadings in overstocked western U.S. forests, the remainder of this project will focus only on mechanical treatments. Mechanical HFR treatments have many benefits over the use of prescribed fire, such as: 1) generally, similar or better treatment effectiveness in bringing fire to the ground; 2) the ability to be used at the WUI without consequences; 3) steady public support; 4) general relative safety; 5) potentially reduced atmospheric carbon emission implications; and 6) the ability to be implemented in a spatially explicit manner (e.g., patterned individual tree removal), which could be of some interest in the future as this area of research progresses.

Mechanical fuel reduction treatments could feasibly be used anywhere, although their use across sensitive sites could be considered detrimental to the overall health of the ecosystem (Fule and Covington 1998). As an overall restoration treatment, mechanical efforts appear to be well-suited and able to remove hazardous fuels without the risk of catastrophic fire. Mechanical removal may be a better option at the WUI and in denser stands with more horizontal continuity (Floyd et al. 2000), and if the ecological implications meet the defined standards of management goals. Other advantages of mechanical treatments are the ability to implement at most any time, the potential for the utilization of the treatment residuals as a resource, the lack of smoke surrounding the treatment area, and reduced CO_2 and other GHG emissions.

1.2 RESEARCH DIRECTION

There are current hazardous forest fuels reduction projects in place that utilize HFR residuals in various ways, mostly by converting small-diameter wood to innovative solidwood products, bioenergy, or a combination of the two in some fashion in order to generate revenue. In the process, the utilization of residuals can have the potential to both store carbon as well as reduce CO_2 emissions to the atmosphere. An added perceived benefit could also manifest itself in the way of increased rates of carbon sequestration in the residual forestland upon treatment, by way of increased growth rates after removing some of the understory competition.

However, the carbon sequestered in the residual stand will be all for naught if a catastrophic, high-intensity wildfire occurs within the forestland after treatment. Therefore, the acceptable likelihood of high-intensity wildfire must be reached by way of the treatment intensity. The interrelation between the factors involved in getting the maximum benefit out of HFR treatments can be daunting in terms of deciding how to treat a given area of at-risk forestland, especially on a project-by-project basis. At the project-level scale, if stand conditions are known and utilization potentials are also known, it may be possible to find an optimal solution to the HFR treatment problem by way of dynamic programming.

1.3 RESEARCH OBJECTIVES

The project objectives are threefold. The first objective is to provide a synthesis of information, consisting of topics related to the utilization of small-diameter timber, forest product carbon chain accounting, carbon storage, and wildfire risk prediction in order to best formulate an objective function for optimization. Once formulated, a second objective is to solve the problem in terms of an optimal management regime to maximize in-forest and wood product carbon storage under the probability of wildfire, with and without the inclusion of fire suppression (Kline et al. 2004). The final objective is to provide a sensitivity analysis to gain a better understanding of which parameters are most important (i.e., those that show the largest effect on the decision-making process). Accomplishing these three objectives will yield a tool that forest managers can utilize to determine what level of treatment is needed based on the current stand conditions and available markets.

1.4 DISSERTATION FORMAT

Chapter 2 outlines the development of a dynamic programming model to account for the probability of wildfire when determining optimal management regimes for maximizing carbon storage within the forest and harvested wood products. The sensitivity of maximum carbon storage management is analyzed for parameters likely to influence regimes. Chapter 3 refines the model by integrating individual-tree distant growth and mortality, dynamic look-up of fire behavior fuel models to dictate fire mortality, and increasing treatment options to cover a range of 0 to 75% of standing basal area reduction by thinning-from-below. Chapter 4 integrates fire spread and fire suppression simulation to determine the impact of stand hillslope position relative to fire access roads on optimal management regimes for maximizing carbon storage within the forest and wood products.

1.5 REFERENCES

Apps, M.J. and D.T. Price. 1996. Introduction. In: Forest Ecosystems, Forest Management, and the Global Carbon Cycle, (M.J. Apps and D.T. Price, eds). NATO ASI Series 1: Global Environmental Changes, Vol. 40, Springer-Verlag, p. 1-15.

Arroja, L., A.C. Dias, and I. Capela. 2006. The role of Eucalyptus globules forest and products in carbon sequestration. Climatic Change 74: 123-140.

Backéus, S., P. Wikström, and T. Lämås. 2005. A model for regional analysis of carbon sequestration and timber production. Forest Ecology and Management 216: 28-40.

Bergman, R. and J. Zerbe. 2004. Primer on wood biomass for energy. USDA Forest Service, State and Private Forest Technology Marketing Unit, Forest Products Laboratory, Madison, WI. 10 p.

Berry, A.H. and H. Hesseln. 2004. The effect of the wildland-urban interface on prescribed burning costs in the Pacific Northwestern United States. Journal of Forestry 102(6): 33-37.

Brockway, D.G., R.G. Gatewood, and R.B. Paris. 2002. Restoring grassland savannas from degraded pinyon-juniper woodlands: Effects of mechanical overstory reduction and slash treatment alternatives. Journal of Environmental Management 64: 179-197.

Brown, S. 2002. Measuring, monitoring, and verification of carbon benefits for forest-based projects. Philosophical Transactions of the Royal Society of London 360: 1669-1683.

Brown, P.M., M.R. Kaufmann, and W.D. Shepperd. 1999. Long-term landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology 14: 513-532.

Brunson, M.W. and B.A. Shindler. 2004. Geographic variation in social acceptability of wildland fuels management in the western United States. Society and Natural Resources 17: 661-678.

Busenberg, G. 2004. Wildfire management in the United States: the evolution of policy failure. Review of Policy Research 21(2): 145-156.

Casperson, J.P., S.W. Pacala, J.C. Jenkins, G.C. Hurtt, P.R. Moorcraft, and R.A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. forests. Science 290(10): 1148-1151.

Chase, A. 2001. In a Dark Wood: The Fight Over Forests and the Myths of Nature. Transaction Publishers 535 pp. ISBN 0765807521

Cuiping, L., Yanyongjie, W. Chuangzhi, and H. Haitao. 2004. Study on the Distribution and quantity of biomass residues resource in China. Biomass & Bioenergy 27(2): 111-117.

Dias, A.C., M. Louro, L. Arroja, and I. Capela. 2005. The contribution of wood products to carbon sequestration in Portugal. Annals of Forest Science 62: 903-909.

Dombeck, M.P., J.E. Williams, and C.A. Wood. 2004. Wildfire policy and public lands: Integrating scientific understanding with social concerns across landscapes. Conservation Biology 18(4): 883-889.

Fiedler, C.E., C.E. Keegan III, D.P. Wichman, and S.F. Arno. 1999. Product and economic implications of ecological restoration. Forest Products Journal 49(2): 19-23.

Fight, R.D., G.L. Pinjuv, and P.J. Daugherty. 2004. Small-diameter wood processing in the southwestern United States: An economic case study and decision analysis tool. Forest Products Journal 54(5): 85-89.

Floyd, L.M., W.H. Romme, and D.H. Hanna. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. Ecological Applications 10(6): 1666-1680.

Fule, P.Z., and W.W. Covington. 1998. Spatial patterns of Mexican pine-oak forests under different recent fire regimes. Plant Ecology 134: 197-209.

Fule, P.Z., A.E.M. Waltz, W.W. Covington, and T.A. Heinlein. 2001. Measuring forest restoration effectiveness in reducing hazardous fuels. Journal of Forestry 99(11): 24-29.

Han, H., H.W. Lee, and L.R. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. Forest Products Journal 54(2): 21-27.

Harmon, M.E. 2001. Carbon sequestration in forests: addressing the scale question. Journal of Forestry 99(4): 24-29.

Harmon, M.E., S.L. Garman, and W.K. Ferrell. 1996. Modeling historical patterns of tree utilization in the Pacific Northwest: carbon sequestration implications. Ecological Applications 6(2): 641-652.

Hashimoto, S., M. Nose, T. Obara, and Y. Moriguchi. 2002. Wood products: potential carbon sequestration and impact on net carbon emissions of industrialized countries. Environmental Science and Policy 5: 183-193.

Heath, L.S., R.A. Birdsey, C. Row, and A.J. Plantinga. 1996. Carbon pools and flux in U.S. forest products. In: Forest Ecosystems, Forest Management, and the Global Carbon Cycle, (M.J. Apps and D.T. Price, eds). NATO ASI Series 1: Global Environmental Changes, Vol. 40, Springer-Verlag, p. 271-278.

Hollenstein, K. R.L. Graham, and W.D. Shepperd. 2001. Biomass flow in western forests. Journal of Forestry 99(10): 12-19.

Karjalainen, T., A. Pussinen, S. Kellomäki, and R. Mäkipää. 1999. Scenarios for the carbon balance of Finnish forests and wood products. Environmental Science and Policy 2: 165-175.

Kline, J.D. 2004. Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the nation's forests. Research Note PNW-RN-542. Corvallis, OR: USDA Forest Service, Pacific Northwest Research Station. 46 p.

Keegan III, C.E., C.E. Fieldler, and T.A. Morgan. 2004. Wildfire in Montana: Potential hazard reduction and economic effects of a strategic treatment program. Forest Products Journal 54(7/8): 21-25.

Keyes, C. and K. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry 17(2): 101-109.

Kline, J.D. 2004. Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the nation's forests. Research Note PNW-RN-542. Corvallis, OR: USDA Forest Service, Pacific Northwest Research Station. 46 p.

Kohlmaier, G., L. Kohlmaier, E. Fries, and W. Jaeschke. 2007. Application of the stock change and the production approach to Harvested Wood Products in the EU-15 countries: a comparative analysis. European Journal of Forest Research 126: 209-223.

Kumar, A., J.B. Cameron, and P.C. Flynn. 2003. Biomass power cost and optimum plant size in western Canada. Biomass & Bioenergy 24(6): 445-464.

Larson, D.S. and R. Mirth. 2004. A case study on the economics of thinning in the wildland-urban interface. Western Journal of Applied Forestry 19(1): 60-65.

Levan-Green, S.L. and J. Livingston. 2001. Exploring the uses for small-diameter trees. Forest Products Journal 51(9): 10-21.

Lim, B., S. Brown, and B. Schlamadinger. 1999. Carbon accounting for forest harvesting and wood products: review and evaluation of different approaches. Environmental Science and Policy 2: 207-216.

Little, J.B. 2003. A light in the forest. American Forests, Winter Issue: 29-32.

Lippke, B., J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Meil. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. Forest Products Journal 54(6): 8-19.

Liski, J., A. Pussinen, K. Pingoud, R. Mäkipää, and T. Karjalainen. 2001. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research 31: 2004-2013.

Lynch, D.L. 2004. What do forest fires really cost? Journal of Forestry 102(6): 42-49.

Malkki, H. and Y. Virtanen. 2003. Selected emissions and efficiencies of energy systems based on logging and sawmill residues. Biomass & Bioenergy 24(4/5): 321-327.

Masera, O.R., J.F. Garza-Caligaris, M. Kanninen, T. Karjalainen, J. Liski, G.J. Nabuurs, A. Pussinen, B.H.J. de Jong, and G.M.J. Mohren. 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling 164: 177-199.

Mason, C.L., B.R. Lippke, K.W. Zobrist, T.D. Bloxton Jr., K.R. Ceder, J.M. Comnick, J.B. McCarter, and H.K. Rogers. 2006. Investments in fuel removals to avoid forest fires result in substantial benefits. Journal of Forestry 104(1): 27-31.

McIver, J.D., P.W. Adams, J.A. Doyal, E.S. Drews, B.R. Hartsough, L.D. Kellogg, C.G. Niwa, R. Ottmar, R. Peck, M. Taratoot, T. Torgersen, and A. Youngblood. 2003. Environmental effects and economics of mechanized logging for fuel reduction in northeastern Oregon mixed-conifer stands. Western Journal of Applied Forestry 18(4): 238-249.

Miller, R.F., and R.J. Tausch. 2002. The role of fire in juniper and pinyon woodlands: A descriptive analysis. IN Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Misc. Pub. No. 11, Tall Timbers Research Station, Tallahassee, FL. pp. 15-30.

Nabuurs, G.J. and R. Sikkema. 2001. International trade in wood products: its role in the land use change and forestry carbon cycle. Climatic Change 49: 377-395.

Nakamura, G. 2004. Biomass thinning for fuel reduction and forest restoration – Issues and opportunities. UC Coop. Extension. http://groups.ucanr.org/forest/.

Niles, J.O. and R. Schwarze. 2001. The value of careful carbon accounting in wood products: Editorial. Climatic Change 49: 371-376.

O'Laughlin, J. and P.S. Cook. 2003. Inventory-based forest health indicators: Implications for national forest management. Journal of Forestry 101(2): 11-17.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as a feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. U.S. Dept. Energy and U.S. Dept. Agriculture http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

Phillips, D.L., S.L. Brown, P.E. Schroeder, and R.A. Birdsey. 2000. Toward error analysis of large-scale forest carbon budgets. Global Ecology and Biogeography 9: 305-313.

Pingoud, K., and F. Wagner. 2006. Methane emissions from landfills and carbon dynamics of harvested wood products: the first-order decay revisited. Mitigation and Adaptation Strategies for Global Change 11: 961-978.

Pingoud, K., B. Schlamadinger, S. Grönkvist, S. Brown, A. Cowie, and G. Marland. 2004. Approaches for inclusion of harvested wood products in future GHG inventories under the UNFCCC, and their consistency with the overall UNFCCC inventory reporting framework. IEA Bioenergy Task 38: Greenhouse Gas Balances of Biomass and Bioenergy Systems. 6 pp.

Pingoud, K. and A. Lehtilä. 2002. Fossil carbon emissions associated with carbon flows of wood products. Mitigation and Adaptation Strategies for Global Change 7: 63-83.

Pingoud, K., A.-L, Perälä, and A. Pussinen. 2001. Carbon dynamics in wood products. Mitigation and Adaptation Strategies for Global Change 6: 91-111.

Richards, K.R. and C. Stokes. 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Climatic Change 63: 1-48.

Schoennagel, T., T.T. Veblen, and W.H. Romme. 2004. The interaction of fire, fuels, and climate across the Rocky Mountain forests. BioScience 54(7): 661-676.

Shindler, B., and E. Toman. 2003. Fuel reduction strategies in forest communities: A longitudinal analysis of public support. Journal of Forestry 101(6): 8-15.

Skog, K.E., K. Pingoud, and J.E. Smith. 2004. A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates. Environmental Management 33(S1): 65-73.

Sohngen, B. and R. Mendelsohn. 2003. An optimal control model of forest carbon sequestration. American Journal of Agricultural Economics 85(2): 448-457.

Waltz, A.E.M., P.Z. Fule, W.W. Covington, and M.M. Moore. 2003. Diversity in ponderosa pine structure following ecological restoration treatments. Forest Science 49(6): 885-900.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313(18): 940-943.

Winter, G.J., C. Vogt, and J.S. Fried. 2002. Fuel treatments at the wildland-urban interface: Common concerns in diverse regions. Journal of Forestry 100(1): 8-15.

Yoder, J. and K. Blatner. 2004. Incentives and timing of prescribed fire for wildfire risk management. Journal of Forestry 102(6): 38-41.

CHAPTER 2

A METHOD FOR MAXIMIZING TERRESTRIAL CARBON DENSITY CONTRIBUTIONS OF WESTERN FORESTS UNDER THE RISK OF WILDFIRE

2.1 ABSTRACT

Current frameworks for analyzing forest carbon offset projects in disturbance-prone western forests often fail to address the dynamic nature of carbon pathways through time. They do not account for the probability of loss due to wildfire, which can influence the prediction of carbon storage at the end of a planning horizon. In such an environment, optimal treatment regimes over time are dependent on the decisions that affect carbon storage during the analysis period. Silvicultural regimes that include both pyrogenic and biogenic emissions from forests, as well as the storage in wood products, were modeled to demonstrate a method to maximize carbon storage.

Stand-level optimization is suggested as a method for demonstrating the development of treatment regimes to enable a full range of carbon storage benefits. These include a reduction in the risk of catastrophic wildfire, increased terrestrial carbon density, and the offset of treatment costs. This methodology may also provide a baseline for a full accounting of forestry carbon offset projects.

The potential for increasing terrestrial carbon density can be limited with the occurrence of intense wildland fire, as exhibited in a simplified simulation model. The optimal carbon storage value was achieved through developing a long-term forest treatment regime that maximized the expected amount of in-forest carbon and carbon in long-lived wood products. The results for this analysis suggest that mechanical forest management treatments that effectively manipulate structure, age, and composition have the greatest potential for maximizing terrestrial carbon stocks by

simultaneously considering both the risk of emission and storage potential. These preliminary results imply that future simulation analyses should account for more of the factors that influence the fluctuation of forest carbon density within the defined boundaries of a terrestrial system, including wildfire risk, the timing and intensity of silvicultural treatments, woody material utilization, and fossil fuel usage.

2.2 INTRODUCTION

Following a century of implementing a successful fire suppression policy in the western United States (Busenberg 2004), the term "healthy forest" has become synonymous with forest conditions that mimic fire regimes found before Euro-American settlement (Adams and Latta 2004). Forests having historical fire regimes of both low- and mixed-severity are commonly being found to be outside of their natural range of variability in terms of mean fire return interval (mFRI). These forests have missed one or several natural-occurring fire cycles and are now often overstocked, making them increasingly prone to larger and more severe wildfires with higher rates of associated mortality (Arno and Fiedler 2005). In mixed-conifer forests, both (mFRI) and natural fire rotation (NFR) are thought to have been shorter before the adoption of fire suppression policy (Taylor and Skinner 1998). These perturbations in the frequency and extent of wildfire have led to increases in stem density, changes in abundance and composition of species more sensitive to frequent fire, and unprecedented accumulations of forest fuels (Taylor and Skinner 2003).

Climate change due to increases in anthropogenic greenhouse gas (GHG) emissions to the atmosphere (Apps and Price 1996) is thought to be correlated with variation in weather patterns (Westerling et al. 2006), wildfire regimes (Taylor et al. 2008), and may directly and indirectly influence future forest vegetation composition and structure. Ever larger and more severe wildfires are predicted for the future due to the potential weather variation (McKenzie et al. 2004) and forest conditions (Taylor and Skinner 2003). Pyrogenic emissions from such fires can become part of a positive feedback loop that serves to further increase levels of atmospheric carbon.

Forests are typically a sink for terrestrial carbon (Goodale et al. 2002), and forest management has been suggested as a possible means of both reducing CO_2 emissions and enhancing carbon sinks (Perez-Garcia et al. 2005, Birdsey et al. 2000). Increasing the terrestrial density of carbon stored in both forests and wood products may have the potential to offset up to 20% of U.S. emissions by the year 2025 (Chameides and Oppenheimer 2007), and entities such as the Chicago Climate Exchange (CCX) and the California Climate Action Registry (CCAR) may act as carbon markets for the efficient reduction of atmospheric carbon inputs from forests (Ruddell et al. 2007). Management objectives include reducing pyrogenic emissions from wildfire and increasing both the proportion and retention of carbon stored in wood products (Birdsey et al. 2000).

Under no-management, the potential exists for continued forest growth and subsequent carbon sequestration (Harmon 2001, Harmon et al. 1990). This will allow a forest to continue accumulating carbon generated through photosynthesis until it is released back to the atmosphere through respiration or the decay of organic matter

(Karjalainen et al. 1999). Until a disturbance event, this scenario results in a forest that acts a net carbon sink until it reaches maturity, and thereafter will essentially fall into CO_2 equilibrium with the atmosphere (Dewar 1991).

However, a no-management scenario in the fire-prone forests of the western U.S. includes the risk of stand-replacing wildfire (and other associated disturbances), and carbon emissions associated with such wildfire can be substantial. Reported values of pyrogenic carbon emissions range from 13 Mg C ha^{-1} to 29 Mg C ha^{-1} (6 to 14% of average forest carbon density) for western mixed-conifer forests, depending on the fire severity (Campbell et al. 2007). Wildfires also cause large biogenic emissions in years following the actual fire (Turner et al. 2007). Sampson and Clark (1996) suggest that biogenic processes stimulated by tree mortality emit an average of five times the original pyrogenic carbon release over the next fifty years following a fire event. In southwestern Oregon (Campbell et al. 2007), post-fire biogenic emissions may range from 30 to 70% of the average forest carbon density. Stand-replacing fire with higher mortality would contribute even greater emissions.

As wildland fire is considered to be a necessary disturbance agent in dry mixed-conifer forests to maintain forest stand dynamics and ecosystem health (Arno and Allison-Bunnell 2002, DeBano et al. 1998, Agee 1993), it is also recognized that current forest conditions, when burned, may not provide similar ecological results when compared to historical outcomes of burning (Carle 2002, Stephenson 1999). The risk of unnaturally severe fire generated by high fuel loadings in these forests restricts the use of natural fires as a primary method to restore forests to their historical conditions (Arno and Fiedler 2005). These concerns support the mechanical manipulation of current forest structure and composition.

Managing forest structure and reducing fuel loads can reduce the risk of high-severity wildfire in forest stands with historically low- and mixed-severity fire regimes, while also reducing the percentage of the landscape that burns severely (Ager et al. 2005, Hollenstein et al. 2001, Graham et al. 1999). Other benefits include the protection of residents and structures at the wildland-urban interface of forestlands and the reduction of fire suppression and post-fire rehabilitation costs (Kline 2004). Mechanical treatments provide for an almost infinite number of potential forest carbon pathways within a planning horizon, but must increase the expected density of terrestrial carbon over time when compared to no-management in order to qualify as a carbon offset project. Without factoring in fluctuations in carbon due to disturbance, the no-management scenario is an inadequate baseline for determining additional carbon storage (Hurteau et al. 2008). Forest carbon pathway analysis has the potential to provide a more realistic baseline for planning purposes, as well as determine silvicultural regimes for the maintenance of more fire-resilient forest structures (North et al. 2007, Gray et al. 2005, Smith et al. 2005, Taylor and Skinner 2003, Waltz et al. 2003).

The development of silvicultural regimes that maximize terrestrial carbon density is dependent on the interaction of several parameters, including: fire occurrence and severity, forest growth and mortality, treatment intensity and type, and utilization of treatment-generated woody material. This interaction can be used to determine an optimal treatment regime that simultaneously considers the risk of emission and storage potential. A mathematical approach that is well suited to solve this type of problem is dynamic programming, due to its ability to determine an optimal sequence of interrelated decisions (Bellman 1957). The carbon loss due to wildfire can be included in the problem as a probabilistic element (Ross 1983). The result is then changed from one that considers the maximum carbon storage to one that considers maximum expected storage, which can then be used as the basis for calculating additional carbon storage.

We explored the optimal management of overstocked dry, mixed-conifer forest stands through three related restoration objectives – the renewal and maintenance of fire-resilient structure, the maximization of terrestrial carbon density, and the offset of treatment costs. An optimal western forest fuel treatment regime is determined under the uncertainty of wildfire, and the ability to include a variety of carbon pathways into a stand-level decision process is demonstrated.

2.3 METHODS

2.3.1 Objective Function Development

To demonstrate the development of an optimal forest treatment regime to maximize carbon storage, dynamic programming (DP) was applied to solve a problem containing two treatment alternatives (no-treatment, 20% basal area reduction per hectare) at each stage for a hypothetical mixed-conifer stand of the western United States. A simple growth model was applied, where basal area was increased at a constant rate over 30 year stages, regardless of treatment or disturbance. To simulate the effect of the silvicultural treatment on tree mortality, given the occurrence of fire, different reduction factors were used in the model. If the stand was treated and a fire occurred, mortality was set to 20% of the standing basal area. Otherwise, if the stand was not treated and a fire occurred, mortality was set to 70% of the standing basal area. A summary of the data and assumptions used in the determination of the optimal treatment regime can be found in Table 2.1.

To track additional carbon storage over the pathway network, standing tree basal area was converted to carbon at a rate of 2.85 Mg per m^2 (Luyssaert et al. 2008, Matthews 1993). A utilization rate was applied to treatment-generated woody material, and material was allocated to end-use classes with corresponding decay rates. Additional carbon values were calculated as the amount of expected carbon at the end of the regime on a dollar per Mg of carbon basis. The objective function used in the problem formulation maximized the expected value of aboveground carbon volume stored in standing trees, woody debris, and wood products due to each decision. Rates for the parameters u_r, u_d, u_w, d_{cwd}, and d_u are shown in Table 2.1, as well as the monetary value of carbon stored in forests and wood products. The objective function applies to the $f_t(s,x_t)$ term found in Equation 2. This function was formulated as follows:

$$f_t(s,x_t) = x_t C[u_r u_d (1-d_u L) + u_w (1-d_{cwd} L) + u_r (1-u_d)] \qquad (1)$$

Where:

$f_t(s,x_t)$ = carbon storage value due to decision x_t at stage t and state s

C = basal area to Mg C conversion

u_r = woody material utilization rate

u_d = fraction of utilized material subject to decay

d_u	= decay rate for utilized woody material
L	= decay horizon ($T - t$)
u_w	= fraction of non-utilized material ($1 - u_r$)
d_{cwd}	= decay rate for non-utilized woody material

2.3.2 Problem formulation

The planning period duration for this example was 90 years, and decisions were made at 30-year intervals over four major stages corresponding to growth periods (t = 1, 3, 5, 6) and two probabilistic stages corresponding to post-fire conditions (t = 2, 4), starting at year 0. At each major stage, two alternatives for each state were possible. Major stage computations followed the following recursive form, where maximum carbon storage for stage t is dependent on the maximum carbon storage for stage t +1:

$$F_t^*(s) = \max_{x_t}[f_t(s, x_t) + F_{t+1}^*(x_t)] \qquad \text{for } t = 1, 3, 5, 6 \qquad (2)$$

Where:

$F_t^*(s)$	= maximum carbon storage for stage t and beyond, given state s at stage t
x_t	= decision variable that determines the destination state at stage t (ba per ha removed at the beginning of stage t)
$f_t(s, x_t)$	= carbon storage value due to decision x_t at stage t and state s
$F_{t+1}^*(x_t)$	= maximum carbon storage value for stage t+1, given decision x_t

Wildland fire was included in the analysis following the first and third stages (Figure 2.1). At these stages, the stand descriptor variable (basal area) was subjected to the decision of no fire occurrence or fire occurrence (Figure 2.1). If there was no fire occurrence, no fire-related mortality was modeled. mFRI was used as a proxy in the determination of fire risk probabilities. According to Finney (2005), NFR is better suited to calculate annual burn probability for some forests because it is defined as the length of time necessary to burn an area the size of a specific area (Agee 1993). However, those forests that are outside the range of historic variability in terms of density and stocking level cannot be expected to behave similarly in terms of NFR (Taylor and Skinner 1998). In this analysis, mFRI is used in conjunction with modeled fire behavior, due to stand conditions, as a measure of fire hazard in order to simulate fire risk. A forested area with an mFRI of 50 years has a probability (p = 0.02) of being exceeded in any one year. Then, the probability of a single fire occurring in that area, over a 30-year stage follows a binomial distribution:

$$P = \binom{n}{r} \times p^{r} \times (1-p)^{n-r} \qquad (3)$$

Where: P = probability that an event happens exactly r times in n successive years

p = probability of event happening per year

In this case, the probability that a fire occurs exactly one time in thirty successive years is 0.334. The probability that a fire does not occur during that time is 1 – 0.334, or 0.666. The expected values for the probabilistic stages are then calculated as follows:

$$F_t^*(s) = [F_{t+1}^*(y_t) \times (1-P) + F_{t+1}^*(y_t+1) \times P] \text{ for } t = 2, 4 \qquad (4)$$

Where: $F_t^*(s)$ = the maximum expected carbon storage value from stage t and beyond, given state s at stage t

y_t = decision variable that determines the destination state at stage t (fire occurrence)

The values obtained during the probabilistic stages represent the expected amount of terrestrial carbon after accounting for the probability of a wildland fire event occurring under specified conditions and assumptions. The result of the fire behavior was expressed as a mortality rate in the alternative generation procedure. In the modeled stand, a decision to reduce basal area carried with it the assumption that fire behavior would be less severe in terms of tree mortality, compared to a no treatment decision. Figures 2.1 and 2.2 show the DP network used in this example and the optimal solution pathway.

By optimizing over a 90-year planning horizon, the maximum expected gross value of carbon at the end of the planning period $F_1^*(i)$ is based on the initial state (i) of the stand:

$$F_1^*(i) = \max_{x_1}[f_1(i, x_1) + F_2^*(x_1)] \qquad (5)$$

Where: $F_1^*(i)$ = maximum expected carbon storage value from stage 1 to the final stage T, given initial state i at stage t

$f_1(i, x_1)$ = carbon storage value due to decision x_1 at stage 1 and state i

$F_2^*(x_1)$ = maximum expected carbon storage value for stage 2, given decision x_1

The results of the model include a series of treatment decisions (i.e., one decision every 30 years), which are expressed as percentage of basal area removed. These decisions are optimal in terms of maximizing expected carbon storage for the simulated treatment scenario and based on the initial parameter values. The model also returns the maximum value of expected carbon storage in Mg C ha^{-1}, as well as the expected carbon storage of the control scenario.

2.4 RESULTS

2.4.1 Optimal Solution

The optimal solution for this problem returned an increase of 6.72 Mg C ha^{-1} in the expected value of stored carbon over the 90 year analysis period. The corresponding treatment prescription involved two removals. The first removed 6.44 m^2 ha^{-1} of basal area in year 0. The second, in year 30, removed 5.93 m^2 ha^{-1} of basal area. The optimal solution did not include a removal at year 60 (Figure 2.1). The no-treatment scenario returned an expected 90-year carbon gain value that was approximately 15.42 Mg C ha^{-1} less than the optimal solution.

2.4.2 Sensitivity Analysis

A partial sensitivity analysis of the optimal solution was carried out to determine how varying one assumption, while holding other assumptions constant, changed the optimal solution. The optimal expected carbon storage is displayed along with values resulting from the no-treatment scenario for comparative purposes.

The sensitivity of carbon storage to the level of fire mortality for the no-treatment scenario was analyzed to establish the relevance of dynamically modeling mortality by predicted fire behavior. Figure 2.3 shows the modeled effect of fire mortality on expected carbon storage for the no-treatment scenario. When the fire mortality factor for the no-treatment scenario is greater than 0.50, there is potential for storing more carbon by treating the stand to keep fire-related mortality at a minimum (e.g., $\leq$ 0.20).

The sensitivity of the optimal solution was also analyzed with respect to mFRI and treatment intensity to determine the relative importance of historical fire frequency and strategically implemented treatment regimes on maximizing carbon storage. Figure 2.4 shows that in stands with a mFRI between approximately 15 and 120 years, the no treatment scenario yielded sub-optimal expected values of carbon storage compared to a treatment regime. Figure 2.5 shows that treatment intensity up to a basal area reduction of 40% yields higher expected values of carbon storage than the no treatment scenario. These analyses are dependent on the constant set of assumed values for fire-related mortality regardless of treatment intensity, but illustrate the need for a dynamic link between the two parameters.

Expected carbon storage was also analyzed for its sensitivity to the utilization level of treatment-generated woody material (Figure 2.6). Utilization levels greater than approximately15% showed more gain in carbon storage by way of a management regime, while levels less than 15% showed the no treatment scenario to store more carbon.

2.4.3 Value Assessment

From a value assessment perspective the average value of carbon used in the analysis was \$5.83 Mg^{-1}, which was based on a study done by Hamilton et al. (2008) for over-the-counter (OTC) carbon trading markets in 2008. The optimal treatment regime showed additional terrestrial carbon stores worth of \$39.19 ha^{-1}, whereas the no-treatment scenario essentially lost a potential \$89.90 ha^{-1} in carbon value. Assuming further that the treatment-generated woody material has a price of \$200 MBF^{-1}, there is potential for creating additional future revenue of approximately \$9,500 ha^{-1} by the end of the planning period through the sale of this material to wood processing facilities. Even though this revenue is partially dependent on actual market value and whether the infrastructure exists for utilizing such material, it is revenue that cannot be captured without actively managing the stand.

2.5 DISCUSSION

2.5.1 Pathway Analysis

The basic principles for the creation of fire-resilient stands (i.e., reducing surface fuels and crown bulk density, increasing crown base height, and protecting large fire-resilient trees) may be achieved by many different methods (Agee and Skinner 2005). Thus, forest carbon can follow different pathways depending on the type of treatment and how prescriptions are implemented over time (Kline 2004). The results of our example forest carbon pathway simulation analyses suggest that the strategic development of a forest management regime can be beneficial in terms of maximizing the amount of terrestrial carbon storage. Under the conditions set in this case, the optimal decision pathway was to the reduce the initial stand from a density of 32.13 m^2 ha^{-1} to a density of 25.69 m^2 ha^{-1} , then treating the stand again at year 30 by 5.93 m^2 ha^{-1} to a density of 23.63 m^2 ha^{-1}. The density of the stand at the end of the final stage (year 90) showed a stand basal area of 31.27 m^2 ha^{-1}. By accounting for the loss due to wildfire and the utilization and decay of the treatment-generated woody material, the optimal decision pathway slightly increased the expected carbon storage by 0.17 Mg C ha^{-1} over a 90-year period when compared to the no-treatment scenario. This is not a significant gain at the unit scale of one hectare. However, if applied to a 1000 hectares of similar forest stand, the 90-year gain is more substantial at 171 Mg C ha^{-1}.

Our work supports the combined research of Petrova et al. (2006) and James et al. (2007), which demonstrates the potential of forest carbon pathway analysis to increase terrestrial carbon density. Petrova et al. (2006) suggest that silvicultural treatments applied to 890,000 hectares of high fire risk California forestlands, which contained an estimated 74 Tg of carbon, could reduce carbon emissions from unnaturally-severe fires by a range of approximately 7 to 51 Tg. That reduction would be equivalent to a range of 40 to 300% of annual net ecosystem production (NEP) for the state of Oregon (Turner et al. 2007). James et al. (2007) showed large differences in mixed-conifer forest carbon density over a 100-year planning horizon between four management scenarios by allowing for carbon stored in wood products. In intensively managed stands, total carbon storage gains ranged from 127% to 166% of forest carbon storage alone.

2.5.2 Parameter Validity

Several important parameters that can influence the optimization of expected carbon storage in fire-prone forests were analyzed for their effect on the model performance: (1) fire-related mortality; (2) mean fire return interval; (3) treatment intensity; and (4) woody material utilization level. Aside from the fact that varying the parameter values will show other optimal results, these four parameters deserve more research in order to determine how they interact within the model structure. Fire-related mortality can be represented dynamically as a function of treatment intensity and other stand condition variables, while mFRI and woody material utilization level are constants that may be manipulated to more accurately simulate the effect of initial stand conditions on optimal carbon storage.

The interaction between fire-related mortality and treatment intensity can be seen through the stand condition state variable, which is represented here as basal area per hectare. For this state variable, it was assumed that the reduction in the density of the stand would reduce the fire-related mortality, and therefore limit carbon emissions compared to a no-treatment decision at the same state. Our results suggest that if all other parameter values are held constant, there is a certain range of fire mortality levels (e.g., ≥ 0.50) associated with the no-treatment decisions where strategic management regimes can increase the expected value of stored carbon over time (Figure 2.3). Introducing a larger set of treatment intensity decision alternatives could show a greater maximum level of expected carbon storage, and can lead to the dynamic determination of fire mortality rates within the model.

The evaluation of the treatment intensity within the current model suggests that decisions at a constant treatment intensity of 40% or less can store more carbon than not managing the stand at all (Figure 2.5). However, representing the treatment intensity as a constant throughout the modeling procedure limits the possible post-treatment stand conditions and the potential fire-related mortality rate in treatment scenarios. Integrating a suite of treatment alternatives to simulate different silvicultural techniques (e.g., thinning-from-below, comprehensive thinning, or species restoration) (Fiedler et al. 1999), and employing a range of treatment intensity levels will provide for many decisions at each stage. This alternative generation technique can lead to a more realistic pathway analysis for the maximization of terrestrial carbon storage, and can be used to strategically implement treatments over time.

Fire mortality will fluctuate as treatment intensity modifies residual stand conditions, and can be characterized by fire behavior fuel models (Scott and Burgan 2005) and stand structure variables such as crown base height and crown bulk density (Keyes and O’Hara 2002). Fuel treatment alternatives can cause changes in crown base height and bulk density, which can be used to determine the susceptibility of a stand to crown fire under a set of specified weather conditions (Keyes and O’Hara 2002). Low thinnings will have a greater effect on the crown base height, while a comprehensive treatment can reduce the crown bulk density. Capturing the complexity inherent within the interaction between fire mortality and treatment intensity will enable an effective strategic decision-making framework for determining optimal management sequences over time.

On a more constant basis, mFRI can be manipulated to produce a range of maximum carbon storage values that could guide treatment regimes in forest stands sensitive to climate change. mFRI is as an influential parameter in our analysis, and it would logically follow that the growth model used to simulate stand conditions should represent a fire regime class that supports the mFRI within the problem. Our assumption of a constant growth rate could be outside of the range of variability for the fire regime class, and matching the growth model to the fire regime class may yield different results. By the mathematical programming method used here, our assumptions suggest that those regimes within the low- to moderate-severity regimes have potential to store more carbon by implementing a management regime over time (Figure 2.4). Adding a stand growth model for Douglas-fir, such as DFSIM (Curtis et al. 1981), can yield optimal management decisions in forests with high-severity fire regimes, while a growth model specific to ponderosa pine (Hann 1980) will better suit a low- and mixed-severity regime.

2.5.3 Capturing Value

Silvicultural treatment can have a large effect on value generation. Forest restoration and comprehensive treatments usually involve a reduction in the density of trees smaller than 20 cm in diameter, while removing a selection of larger-diameter trees (Fight et al. 2004). The larger-diameter trees can be converted into solidwood products and can have substantial value in sawlogs, whereas small-diameter trees have traditionally been left at the treatment site. Fiedler et al. (1999) reported higher net revenue values from the implementation of a comprehensive restoration treatment when compared to a thin-from-below treatment that only removed smaller diameter material. The comprehensive treatment utilized free thinning, which included a low thinning of diameters less than 23 cm, a modified selection cutting to restore uneven-aged structure, and an improvement cutting to remove non-historic species. A comprehensive treatment may also better approximate historic forest structure and function, as it addresses the lack of flexibility in addressing species variation by rigid stand-wide upper-diameter limits described by North et al. (2007).

Value can also be captured through efficient sorting and processing if the infrastructure and markets are in place (Hartsough et al. 2001, LeVan-Green and Livingston 2001, Fiedler et al. 1999). The value of treatment-generated material is dependent on the size and species of the woody material, the amount and size of knots, and other defects. Value may also be dependent on by-products from processing (Fight et al. 2004). Examples of by-product utilization include chips for bioenergy fuel, pulp for paper, sawdust for medium-density fiberboard, and the use of chips or sawdust for landscaping applications, animal bedding, or as a soil amendment (James et al. 2007). These factors influence the optimal product mix in terms of value generation.

The value associated with the utilization of treatment-generated material can be further influenced by the determination of optimal forest restoration regimes. The removal of larger-diameter trees is likely to have the most effect on revenue, but the effective utilization of smaller treatment-generated woody material also has an effect on value recovery. The conversion of woody material into value-added products such as flooring and millwork, non-traditional products such as non-structural lumber, posts/poles, grape stakes, and the further utilization of processing by-products will be an important factor for offsetting forest treatment costs. The optimal utilization of woody material, in terms of value generation, will depend on the availability and size of wood product markets.

2.5.4 Utilization Assumptions

Our model suggests that utilization rates may have to be around 70% or greater for a treatment regime to store more carbon than a no treatment scenario (Figure 2.6). The ability of the local or regional area to utilize treatment-generated woody material may not reach this rate, and could affect the expected value of maximum carbon that can be achieved. Material is processed into long-lived wood products that have a lifespan and an end use, both of which will determine the amount and rate of decay for utilized woody material. Also, the amount and type of woody material that can be removed from the treated area will affect the residual stand condition, and could possibly influence the choice of fire behavior fuel models and predicted mortality level. With the rise of community-based wood utilization centers and sorting yards, the level of utilization efficiency could increase, having a positive effect on maximum carbon storage.

The Petrova et al. (2006) study concentrated on forested areas that could be relatively easily treated (i.e., of moderate slope, within 400 meters of existing roads, and within 80 km of an existing processing facility), and James et al. (2007) focused on privately-owned timberlands with infrastructure in place. Stands that are too far from existing roads or processing facilities may not return revenue, or benefit from treatment in terms of carbon storage. Carbon emissions from fossil fuel consumption during thinning methods, transportation, primary and secondary processing, and distance travelled to wood product end use stand to decrease the level of maximum carbon storage expected from treatment regimes. Minimizing fossil fuel consumption throughout the regime should be a goal for forest engineers already, as it adds a cost to each process. Optimization of the transportation and harvesting systems may increase efficiency and decrease the overall amount of fuel consumption.

2.6 CONCLUSION

Overall, the current model suggests that gains in terrestrial carbon storage can be accomplished at the stand level by optimal management regimes. However, these gains are restricted to stands with a low- to mixed-fire regime and are influenced by treatment intensity, predicted fire mortality, and treatment-generated woody material utilization. The determination of optimal silvicultural regimes for maximizing carbon storage is also incomplete without addressing the uncertainty that surrounds the random nature of fire as disturbance within western forests. In the case of wildfire, we are uncertain as to the amount of carbon that will be stored over time because it depends on the occurrence of fire (Hurteau et al. 2009). However, we do know the probability of occurrence, which carbon storage is a function of in terms of pyrogenic emissions and tree mortality. Our probabilistic dynamic programming approach utilizes the fire occurrence probability function to optimize silvicultural treatments under such uncertainty.

The objective for many forest restoration activities in fire-prone western forests should include the preparation of stands for the return of a low- or mixed-fire severity regime. The restoration of western forests to active-fire conditions may seem counterproductive to increasing terrestrial carbon density, as pyrogenic emissions contribute to atmospheric GHG concentrations. However, conservative estimates show that carbon emissions from high-severity wildfire are upwards of two to four times the magnitude of low- to moderate-severity wildfire (Campbell et al. 2007, Kasischke and Bruhwiler 2003), while a stand-replacing fire contributes an even greater amount of carbon to the atmosphere. Implementing mechanical treatments to create stands more resilient to active or passive crown fire is a major step in restoring functional active-fire conditions (Graham et al. 2004), and as indicated in these results, may store greater amounts of carbon in trees and wood products over time than no treatment at all. If reducing atmospheric carbon levels is an objective, then a silvicultural regime that minimizes fire-related emissions by reducing the probability of high-severity or even stand-replacing wildfire can be beneficial in fire-prone western forests.

This analysis suggests that, while there are many pathways for forest carbon to travel in fire-prone forests, the optimal pathway for maximizing carbon density over time is dependent on factors related to stand conditions. An optimal silvicultural regime reduces the risk of high-severity wildfire and fire-related mortality in low- to mixed-severity regimes within our model. When stand conditions are conducive for crown fires and higher rates of associated mortality, strategically treating the stand and utilizing the treatment-generated woody material can lead to greater values of carbon storage than not treating the stand. The implementation of an optimal treatment regime can also be financed by its own value if infrastructure and markets are in place. This analysis also suggests that further research efforts should develop the carbon relationships between the treatment intensity, stand condition, and fire mortality.

2.7 REFERENCES

Adams, D.M. and G.S. Latta. 2004. Effects of a forest health thinning program on land and timber values in eastern Oregon. Journal of Forestry 102(8): 9-13.

Agee, J.K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Agee, J.K. and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Ager, A.A., R.J. Barbour, and J.L. Hayes. 2005. Simulating fuel reduction scenarios on a wildand-urban interface in northeastern Oregon. In: Bevers, M. and T.M. Barrett, comps. Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium. USDA Forest Service Gen. Tech. Rep. PNW-GTR-656. Portland, OR. pp. 215-227.

Apps, M.J. and D.T. Price. 1996. Introduction. In: Forest Ecosystems, Forest Management, and the Global Carbon Cycle, (M.J. Apps and D.T. Price, eds). NATO ASI Series 1: Global Environmental Changes, Vol. 40, Springer-Verlag, pp. 1-15.

Arno, S.F. and C.E. Fiedler. 2005. Mimicking Nature's Fire: Restoring Fire-Prone Forests in the West. Island Press, Washington, DC.

Arno, S.F. and S. Allison-Bunnell. 2002. Flames in Our Forest: Disaster or Renewal? Island Press, Washington, D.C.

Bellman, R. E. 1957. Dynamic Programming. Princeton University Press, Princeton, New Jersey. 340 p.

Birdsey, R., R. Alig, and D. Adams. 2000. Mitigation activities in the forest sector to reduce emissions and enhance sinks of greenhouse gases. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-59 pp. 112-131.

Busenberg, G. 2004. Wildfire management in the United States: the evolution of policy failure. Review of Policy Research 21(2): 145-156.

Campbell, J., D. Danato, D. Azuma, and B. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, United States. Journal of Geophysical Research 112, G04014, doi: 10.1029/2007JG000451.

Carle, D. 2002. Burning Questions: America's Fight with Nature's Fire. Praeger Publishers, Westport, CT.

Chameides, W. and M. Oppenheimer. 2007. Carbon trading over taxes. Science 315(5819): 1670.

Curtis, R.O., G.W. Clendenen, and D.J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. Gen. Tech. Rep. PNW-128. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Research Station. 79 p.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 1998. Fire's Effects on Ecosystems. John Wiley & Sons, Inc., New York.

Dewar, R.C. 1991. Analytical model of carbon storage in the trees, soils, and wood products of managed forests. Tree Physiology 8: 239-258.

Fiedler, C.E., C.E. Keegan, D.P. Wichman, and S.F. Arno. 1999. Product and economic implications of ecological restoration. Forest Products Journal 49(2): 19-23.

Fight, R.D., G.L. Pinjuv, and R.J. Daugherty. 2004. Small-diameter wood processing in the southwestern United States: an economic case study and decision analysis tool. Forest Products Journal 54(5): 85-89.

Finney, M.A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management 211: 97-108.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.J. Kohlmaier, W. Kurz, S. Liu, G. Nabuurs, S. Nilsson, and A.Z. Shvidenko. 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications 12(3): 891-899.

Graetz, D. and P. Bettinger. 2005. Determining thinning regimes to reach stand density targets for any-aged stand management in the Blue Mountains of eastern Oregon. In: Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium, (Bevers, M. and T.M. Barrett, eds). USDA Forest Service Gen. Tech. Rep. PNW-GTR-656. Portland, OR. pp. 255-264.

Graham, R.T., S. McCaffrey, and T.B. Jain. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service Gen.Tech. Rep. GTR-RMRS-120. Fort Collins, CO. 43 p.

Graham, R.T., A.E. Harvey, T.B. Jain, and J.R. Tonn. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Service PNW-GTR-463. Portland, OR. 27 p.

Gray, A.N., H.S.J. Zald, R.A. Kern, and M. North. 2005. Stand conditions associated with tree regeneration in Sierran mixed-conifer forests. Forest Science 51(3): 198-210.

Hamilton, K., M. Sjardin, T. Marcello, and G. Xu. 2008. Forging a frontier: state of voluntary carbon markets 2008. A report by Ecosystem Marketplace and New Carbon Finance. Forest Trends Association, Washington, D.C.

Hann, D. 1980. Development and evaluation of an even- and uneven-aged ponderosa pine/Arizona fescue stand simulator. USDA Forest Service Res. Pap. RP-INT-267. 95 p.

Harmon, M.E. 2001. Carbon sequestration in forests: addressing the scale question. Journal of Forestry 99(4): 24-29.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247: 699-702.

Hartsough, B.R., X. Zhang, and R.D. Fight. 2001. Harvesting cost model for small trees in natural stands in the interior Northwest. Forest Products Journal 51(4): 54-61.

Hollenstein, K., R.L. Graham, and W.D. Shepperd. 2001. Biomass flow in western forests: simulating the effects of fuel reduction and presettlement restoration treatments. Journal of Forestry 99(10): 12-19

Hurteau, M.D., B.A. Hungate, and G.W. Koch. 2009. Accounting for risk in valuing forest carbon offsets. Carbon Balance and Management 4(1) doi:10.1186/1750-0680-4-1

Hurteau, M.D., G.W. Koch, and B.A. Hungate. 2008. Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Frontiers in Ecology and the Environment *In Press* doi:10.1890/070187

James, C., B. Krumland, and P.J. Eckert. 2007. Carbon sequestration in California forests; two case studies in managed watersheds. Report furnished to Sierra Pacific Industries Forestry Division, PO Box 496014, Redding, CA 96049-6014.

Karjalainen, T., A. Pussinen, S. Kellomäki, and R. Mäkipää. 1999. Scenarios for the carbon balance of Finnish forests and wood products. Environmental Science and Policy 2: 165-175.

Kasischke, E.S. and L.P. Bruhwiler. 2003. Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. Journal of Geophysical Research 107: 1-14.

Keyes, C.R. and K.L. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry 17(2): 101-109.

Kline, J.D. 2004. Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the nation's forests. Research Note PNW-RN-542. Corvallis, OR: USDA Forest Service, Pacific Northwest Research Station. 46 p.

LeVan-Green, S.L. and J. Livingston. 2001. Exploring the uses for small-diameter trees. Forest Products Journal 51(9): 10-21.

Luyssaert, S., E. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law, P. Ciais, and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature 455(7210): 213-215.

Matthews, G. 1993. The carbon content of trees. In: Forestry Commission Technical Paper 4, Edinburgh, UK: Forestry Commission.

McArdle, R.E., W.H. Meyer, and D. Bruce. 1961. The yield of Douglas-fir in the Pacific Northwest. US Department of Agriculture Technical Bulletin 201. Washington, D.C. 74 p.

McKenzie, D., Z. Gedalof, D.L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18(4): 890-902.

North, M., M. Hurteau, R. Fiegener, and M. Barbour. 2005. Influence of fire and El Niño on tree recruitment varies by species in Sierran mixed conifer. Forest Science 51(3): 187-197.

North, M., J. Innes, and H. Zald. 2007. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. Canadian Journal of Forest Research 37(2): 331-342.

Perez-Garcia, J., B. Lippke, J. Comnick, and C. Manriquez. 2005. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science 37: 140-148.

Petrova, S., N. Martin, S. Brown, and J. Kadyszewski. 2006. Carbon supply from changes in management of forests, range, and agricultural lands of California: Forest fuel reduction. Winrock International for the California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-093-AD.

Ross, S.M. 1983. Introduction to Stochastic Dynamic Programming. Academic Press, Inc. New York, New York. 164 p.

Ruddell, S., R. Sampson, M. Smith, R. Giffen, J. Cathcart, J. Hagan, D. Sosland, J. Godbee, J. Heissenbuttel, S. Lovett, J. Helms, W. Price, and R. Simpson. 2007. The role for sustainably managed forest in climate change mitigation. Journal of Forestry 105(6): 314-319.

Sampson, R.N. and L.R. Clark. 1996. Wildfire and carbon emissions: A policy modeling approach. Chapter 13 in Forests and Global Change Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. Edited by R.N. Sampson and S. Hair. American Forests Publication; Washington, D.C.

Scott, J.H. and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermal's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: USDA, Forest Service, Rocky Mountain Research Station. 72 p.

Smith, T.F., D.M. Rizzo, and M. North. 2005. Patterns of mortality in an old-growth mixed-conifer forest of the southern Sierra Nevada, California. Forest Science 51(3): 266-275.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forest of western Oregon and Washington. Ecology 69(6): 1689-1702.

Stephens, S.L. and J.J. Moghaddas. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215: 21-36.

Stephenson, N.L. 1999. Reference conditions for giant sequoia forest restoration: structure, process, and precision. Ecological Applications 9(4): 1253-1265.

Taylor, A.H. and C.N. Skinner. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management 111: 285-301.

Taylor, A.H. and C.N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structures in the Klamath Mountains. Ecological Applications13(3): 704-719.

Taylor, A.H., V. Trouet, and C.N. Skinner. 2008. Climatic influences on fire regimes in montane forests of the southern Cascades, California, USA. International Journal of Wildland Fire 17: 60-71.

Turner, D.P., W.D. Ritts, B.E. Law, W.B. Cohen, Z. Yang, T. Hudiberg, J.L. Campbell, and M. Duane. 2007. Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. Biogeosciences 4: 597-612.

Waltz, A.E.M., P.Z. Fulé, W.W. Covington, and M.M. Moore. 2003. Diversity in ponderosa pine forest structure following ecological restoration treatments. Forest Science 49(6): 885-900.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313(18): 940-943.

Winjum, J.K., S. Brown, and B. Schlamadinger. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. Forest Science 44(2): 272-284.

Ximenes, F.A., W.D. Gardner, and A.L. Cowie. 2008. The decomposition of wood products in landfills in Sydney, Australia. Waste Management *In Press* doi:10.1016/j.wasman.2007.11.006

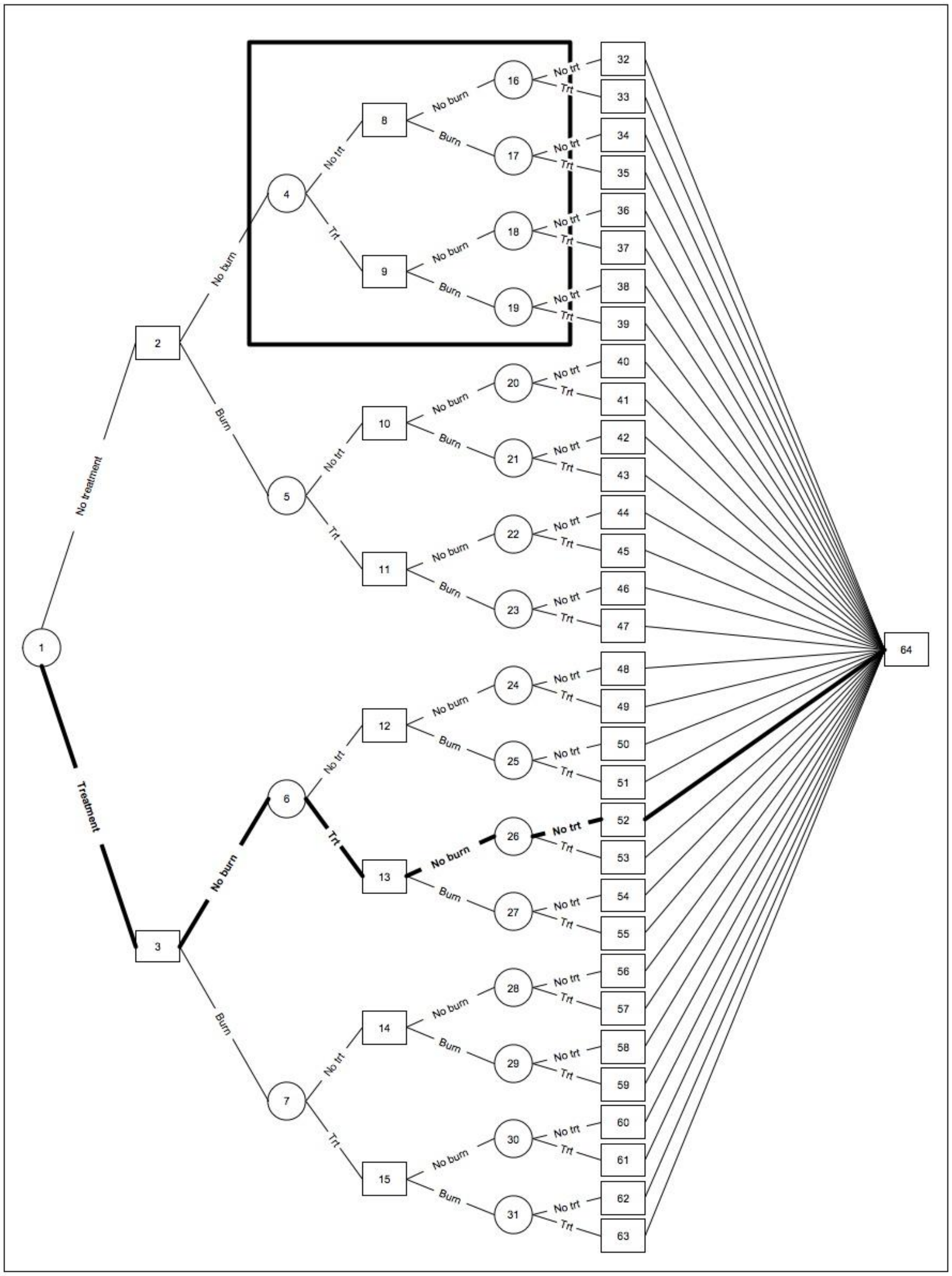

Figure 2.1 – Dynamic programming network & optimal solution for example problem (boxed area found in figure 2)

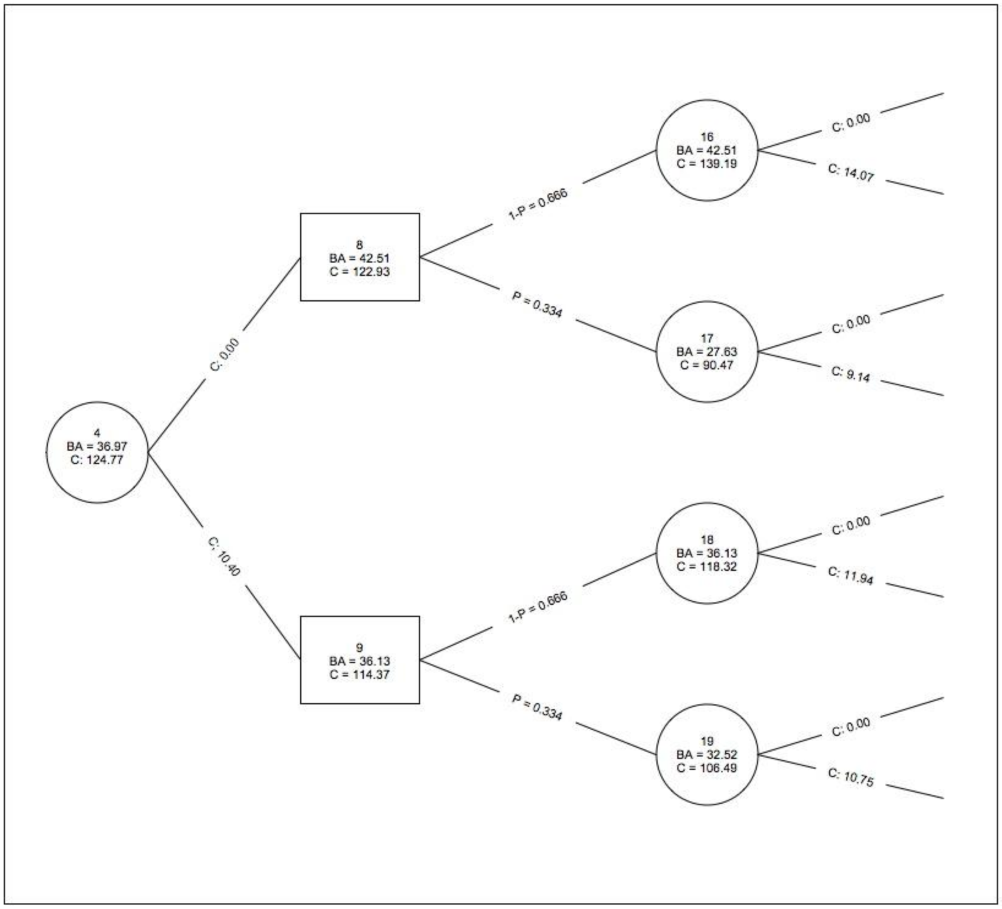

Figure 2.2 – Detail of probabilistic dynamic programming network

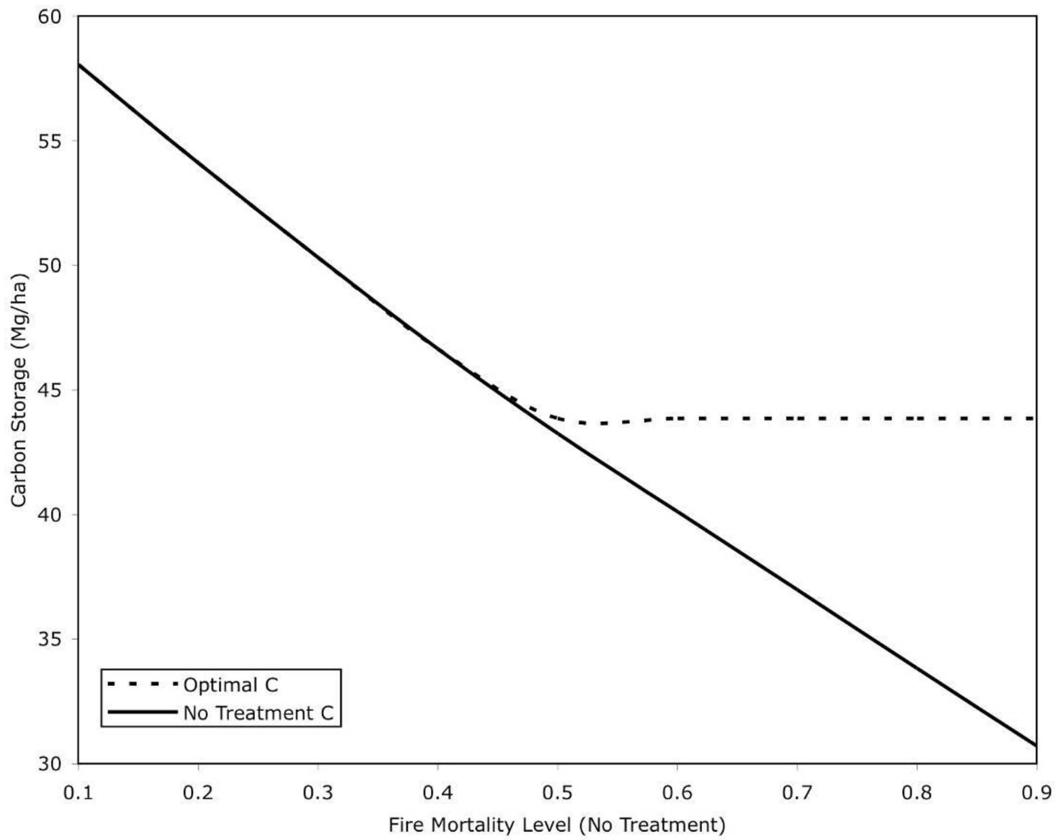

Figure 2.3 – Sensitivity of carbon storage to the no treatment scenario fire mortality level

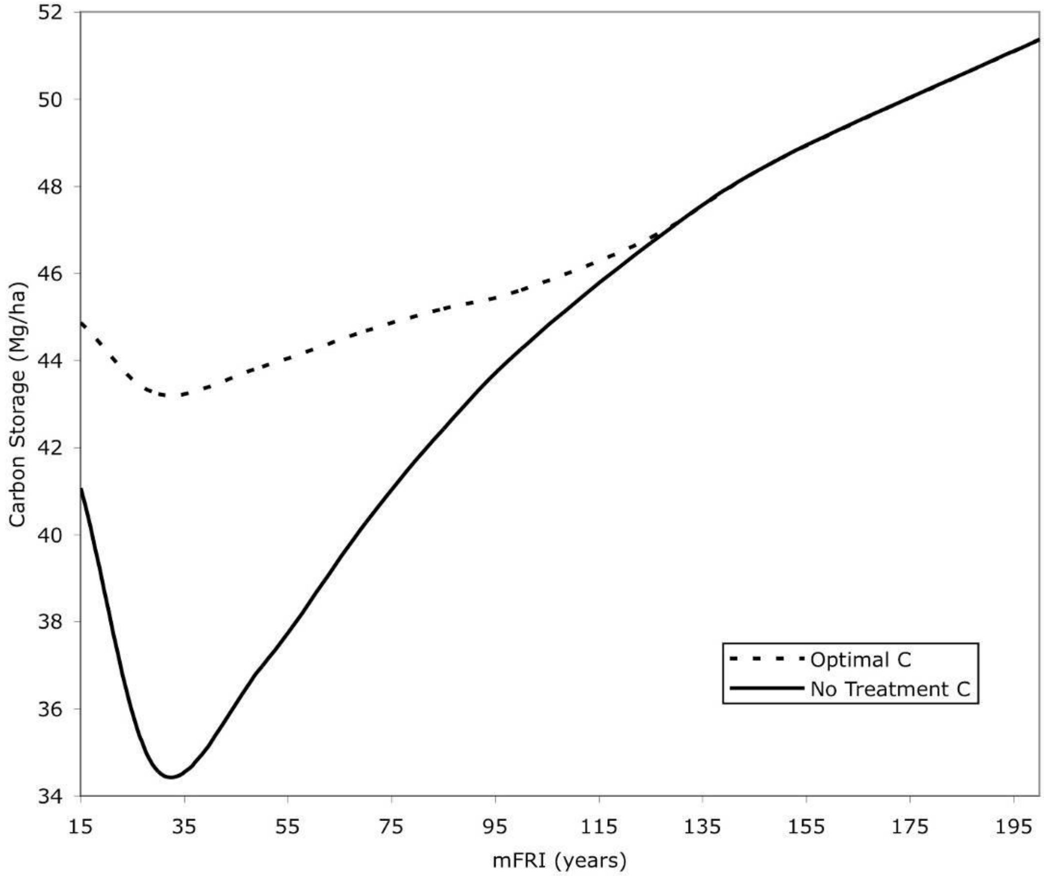

Figure 2.4 – Sensitivity of carbon storage to mean fire return interval

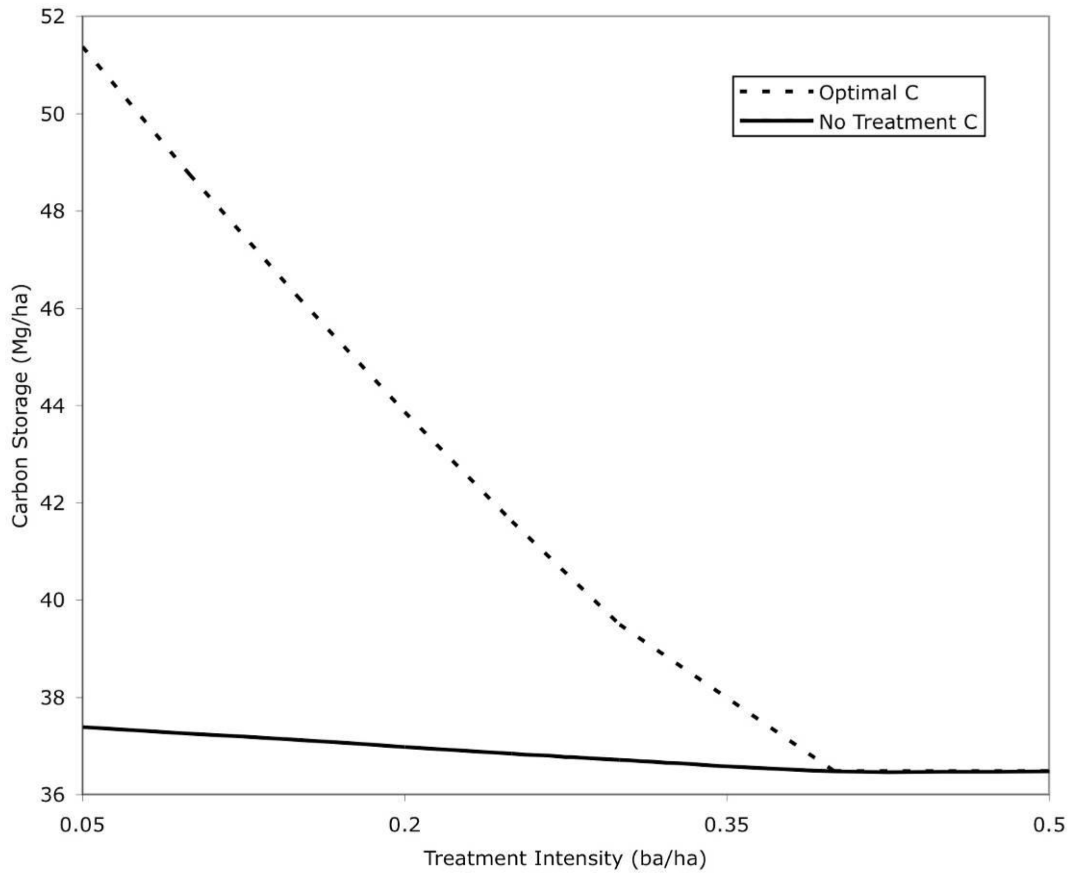

Figure 2.5 – Sensitivity of carbon storage to treatment intensity

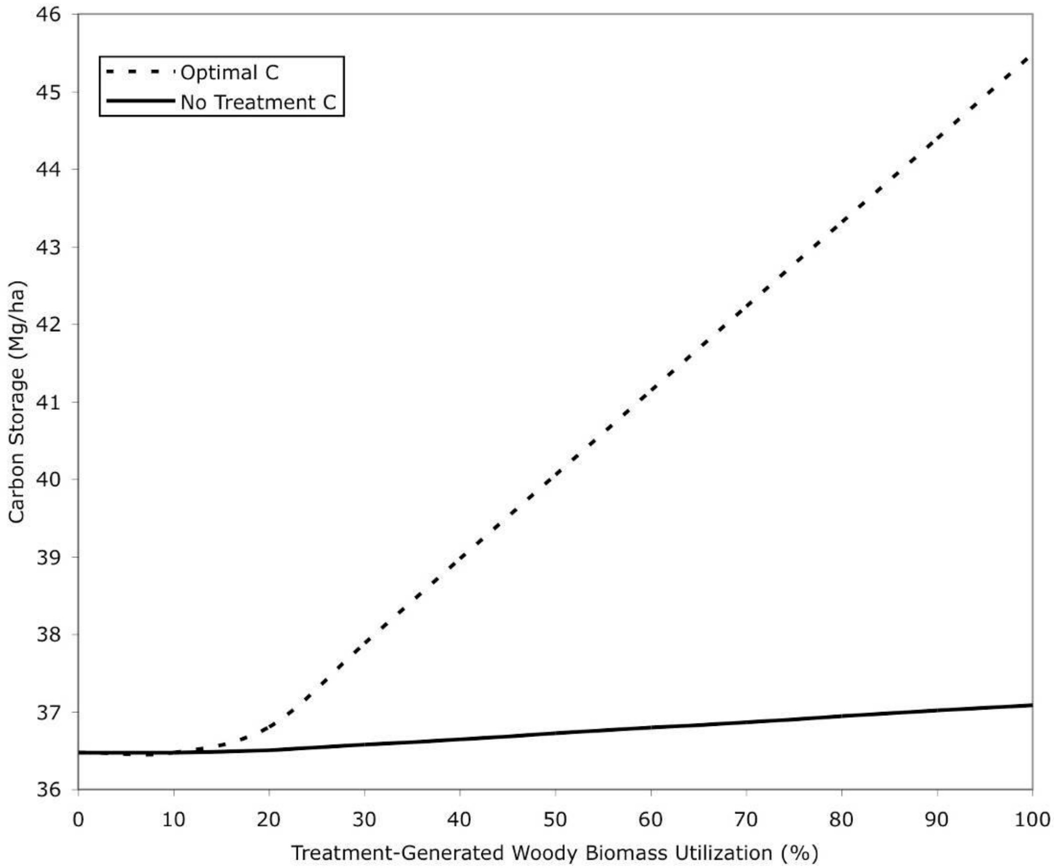

Figure 2.6 – Sensitivity of carbon storage to biomass utilization rate

Table 2.1 – Summary of data and assumptions used in the determination of optimal treatment regime

30-year ba/ha growth rate (McArdle et al. 1961)	**1.15**
Fraction of treatment ba/ha removal (Stephens and Moghaddas 2005)	**0.2**
Fire mortality fraction for no-treatment decision (Stephens and Moghaddas 2005)	**0.7**
Fire mortality fraction for treatment decision (Stephens and Moghaddas 2005)	**0.20**
Stand FRI (Taylor and Skinner 2003, 1998)	**50 years**
Initial stand ba/ha (Graetz and Bettinger 2005)	**32.13 m^2**
Woody material utilization rate (James et al. 2007)	**0.85**
Utilized woody material annual decay rate (Winjum et al. 1998)	**0.01**
Non-utilized woody material annual decay rate (Spies et al. 1988)	**0.029**
Fraction of utilized material subject to decay (James et al. 2007)	**0.75**
Fraction of utilized material permanently stored (Ximenes et al. 2008)	**0.25**
Carbon Value (Hamilton et al. 2008)	**$5.83/Mg**
ba/ha to carbon volume conversion (Luyssaert et al. 2008, Matthews 1993)	**2.85 Mg/m^2**

CHAPTER 3

ENHANCING ABOVEGROUND TERRESTRIAL CARBON STOCKS IN FIRE-PRONE NATURAL SYSTEMS: OPTIMAL MANAGEMENT REGIMES FOR WESTERN OREGON FOREST STANDS

3.1 ABSTRACT

In response to increasingly volatile forest conditions in terms of wildfire intensity and severity in western forests and concerns over carbon emissions to the earth's atmosphere, a model was developed to determine optimal management regimes that maximize the expected value of terrestrial carbon storage for three fire-prone forests. Carbon storage values for treatment combinations were weighted by the probability of fire occurrence and the loss of carbon due to fire. The model employs dynamic programming to determine the optimal timing and intensity of silvicultural treatments by way of thinning-from-below.

Our results support the concept that light low thinning-type fuel treatments, when modeled over time, can result in additional carbon storage in some fire-prone western forests when compared to control scenarios. It further suggests that a combination of let-grow and low-level density reduction decisions over time can store more aboveground terrestrial carbon in both forests and long-lived wood products than grow-only control scenarios across several forest types. The additional expected carbon storage by way of fire risk management activity compared to the control ranged from 0 to 170.31 Mg ha^{-1}. Maximum values for low thinnings were 15% of standing tree basal area.

Optimal treatment regimes stored more terrestrial carbon than control solutions, and exhibiting carbon market values ranging from $0 to $990 per hectare. Additional expected carbon storage of optimal solutions compared to the 100-year gain for control scenarios ranged from 0 to 43%. This suggests that strategic planning

by the optimization model can compete with the hedge method of the Voluntary Carbon Standard risk management, which employs carbon buffer pools to compensate for the risk associated with disturbance and can require the size of the buffer deposit to range from 10 to 60% of the generated carbon credits, depending on the risk class determined for a given project.

3.2 INTRODUCTION

Forests in the United States are currently a carbon sink, which sequester approximately 10% of U.S. annual carbon dioxide (CO_2) emissions (Birdsey et al. 2006). However, Ruddell et al. (2007) suggest that higher (i.e., "additional") levels of carbon storage could be achieved by way of improved forest management that departs from business as usual (i.e., "baseline") conditions. While there has been some research on the impact of forest management on aboveground terrestrial carbon storage (Davis et al. 2009, Nunery and Keeton 2010), there is little information on the strategic decision-making of management actions in order to meet the objective of increasing such carbon stocks over time. A decision support system is an important tool for meeting the objective of increasing forest-based aboveground terrestrial carbon stocks because the carbon dynamics associated with forest management and the utilization of management-generated woody material are complex and therefore present a nearly infinite number of possible management regimes (i.e., a sequential set of silvicultural decisions over a planning horizon) for stakeholders to consider. In the absence of decision support, management activities are many times, by definition, sub-optimal in terms of performance in meeting objectives due to the inability to analyze the vast range of available management regimes.

This potential to optimize the performance of management activities to meet specific objectives is vital to the research directive of the U.S. Forest Service, which has been recently been placed entirely within the context of responding to climate change. Based on the new directive, decision support systems are needed to integrate strategies to address climate change, and must encompass both facilitated adaptation to reduce the impacts associated with climate change as well as mitigation efforts to reduce the perceived causes of climate change (Solomon et al. 2009). Natural adaptations are expected to be unable to keep up with the rate of climate change; therefore, potential adaptation strategies include the management of forests to create structures resilient to climate-altered disturbance events, while mitigation strategies include increasing the amount of carbon storage in forests, soils, and wood products (Solomon et al. 2009). Furthermore, since forests are carbon sinks that are relatively simple to manipulate, they are also prime candidates for the development of management regimes that apply principles of strategic adaptation (e.g., density reduction treatments) to maximize mitigation objectives (e.g., increased aboveground terrestrial carbon storage).

The fire-prone forests of the western U.S. potentially have the most to gain from a decision support system to maximize aboveground carbon storage, due to their high rates of biomass accumulation and the role of fire as a disturbance. Many forest stands of the western U.S. are overstocked in terms of tree density, which is leading towards wildfires that are more severe in intensity and resulting in a greater mortality rate that departs from natural historical patterns (Arno and Fiedler 2005). The pairing of climate change adaptation and mitigation strategies relate favorably to the management of western fire-prone forests that are affected by this observed deviation in fire behavior.

For example, the manipulation of forest stand structure in the Pacific Northwest has been suggested to positively influence aboveground carbon storage over a century of growth when compared no management activity (Hurteau and North 2009). This result can be attributed to the effect of forest structure manipulation on stand dynamics and fire behavior in mixed-conifer stands (North et al. 2009). Reinhardt and Holsinger (2010) suggest that management activity has the opposite effect on the aboveground carbon storage of most forests in the northern Rocky Mountain region of the U.S. when including the resultant fire behavior in the analysis. However, close inspection of the results imply that mechanical thinning-from-below treatments that manipulate stand structure in ponderosa pine forests can have net positive effects on carbon storage over a 90-year period when compared to no-treatment scenarios, Nunery and Keeton (2010) propose that management activity in the northeastern U.S. leads to decreases in forest-based aboveground carbon storage, but the analysis does not include the influence of fire or other disturbance events on carbon dynamics. Chen et al. (2010) do include the risk of wildfire within their landscape level analysis of managed forests in Ontario, Canada, and conclude that forest-based terrestrial carbon density will increase over the next century. These results suggest that the inclusion of the risk of aboveground carbon loss from wildfire into the strategic planning process can influence the optimal timing and intensity of management activity, which provides the potential for the opportunity to maximize forest-based contributions to terrestrial carbon density.

The risk of carbon loss is already a major component of burgeoning carbon markets based on Improved Forest Management (IFM) projects under the Voluntary Carbon Standard (VCS 2008). However, the risk analysis in place for projects adhering to the VCS only guards against potential loss by the maintenance of a carbon buffer pool (Hurteau et al. 2009). Furthermore, the size of the required buffer deposit can range from 10 to 60% of the generated carbon credits, depending on the risk class determined for a given project (VCS 2008). While the VCS method of risk analysis accounts for potential carbon losses due to natural disturbances, it does not incorporate risk into the management strategy to actively avoid terrestrial carbon losses. Therefore, the VCS method of risk management for IFM fails to maximize the potential of fire- or disturbance-prone forests to increase terrestrial carbon density over the typical carbon offset project with analysis periods greater or equal to 100 years in duration.

This paper reports optimal 100-year management regimes for three Douglas-fir *(Pseudotsuga menziesii)* dominated forest types in western Oregon, USA. Silvicultural treatments were simulated to manipulate stand structure and composition. Treatment effects on growth, fire behavior, and mortality were modeled to create decision networks that represent stages of stand dynamics at discrete time intervals, and dynamic programming was used to mathematically determine optimal pathways from the decision networks. The timing and intensity of silvicultural treatments to maximize the expected value of forest-based terrestrial carbon stocks are reported for stands subject to the probabilistic occurrence of wildfire. The Stand Visualization System (SVS) was used to simulate the effects of optimal management regimes on changes in forest carbon stocks and stand structure for the best-performing solution of all forest types, as well as to visually validate the results of the probabilistic optimization model. Control solutions were also simulated in SVS for comparing forest structures to the best-performing solution.

3.3 METHODS

3.3.1 Stand Sample Selection

Optimal management regimes were computed at the stand level for three Douglas-fir dominated forest types in western Oregon (Hann et al. 2004, Schmidt et al. 2002) (Figure 3.1). Forest types were chosen based on fire ecology, species composition, and other biophysical settings (Table 3.1). Ten plot samples for each of the three forest types were selected from the Forest Inventory and Analysis (FIA) database (http://fia.fs.fed.us) based on both stand age and density (Table 3.2). Plot samples were restricted to mature stands between the ages of 40 and 140 years to ensure the performance of the growth and mortality model (Curtis 1994). Stands were also restricted to those with tree densities sufficient to make silvicultural treatments feasible, and stands with basal areas below minimum densities were excluded from the analysis.

3.3.2 Silvicultural Treatments

In order to mimic changes in forest structure, silvicultural treatments were simulated as low thinnings with a range from 15 to 75% reduction in stand basal area at intervals of 15%. The inclusion of low thinning treatments across a range of intensities allowed for the representation of changes in forest composition, by simulating the removal of younger trees of species other than those that are more mature. The harvest system is assumed to be comprised of a harvester for felling, delimbing, and topping, coupled with either a grapple skidder or a small forwarder for extraction purposes. Treatment-generated leaves, branches, and tops are gathered and either burned onsite or chipped and burned for fuel, while harvested tree stems are removed for processing into wood products. Wood processing removes the bark to be combusted for fuel purposes, and allocates biomass to either long-term or short-term product and by-product storage pools. Lumber is allocated to long-term storage, as are shavings and a significant portion of sawdust. The remaining sawdust and any chips are allocated to short-term storage, and are assumed to be combusted for fuel. Estimation equations (Jenkins et al. 2003) and values for these biomass parameters (J. Reeb, personal communication 2011), as well as their decay functions (Winjum et al. 1998, Spies et al. 1988) are compiled in Table 3.6.

To simulate the effect of no management activity on a stand, a treatment was included to serve as a growth and mortality control. Six treatments per 10 stand samples were applied to each of the three forest types for a total of 180 initial condition treatment analysis combinations, 30 of which were grow-only control scenarios.

3.3.3 Forest Stand Dynamics Simulation

Stand growth and growth-related mortality were modeled with ORGANON (Zumrawi and Hann 1989, Hann and Wang 1990, Ritchie and Hann 1990, Hann and Larsen 1991, Zumrawi and Hann 1993) because of its consistently conservative estimates (Curtis 1994). Tree crown radius, canopy cover, and crown competition were determined by way of models built by Gill et al. (2000). These models and equations, along with ORGANON stand growth and mortality expressions, were coded in Microsoft Visual C++ as functions to develop a model to support decision network generation within the dynamic programming optimization program.

Silvicultural treatments were applied to the initial stand conditions at the beginning of each decision stage, and post-treatment stand growth and mortality were simulated on annual intervals and accumulated over 10-year periods to coincide with the decision stages of the algorithm procedure. The 10-year period was also used in attempt to standardize the treatment interval used in previous research (Mitchell et al. 2009, Graetz and Bettinger 2005). Growth and mortality, as calculated by the ORGANON individual-tree distant-independent model, was allocated to diameter classes at the hectare level. This allowed for the modeling of stand dynamics at the individual-tree level, and a summary of tree statistics scaled at the stand level.

3.3.4 Fire Behavior and Mortality Simulation

Fire behavior fuel models (Scott and Burgan 2005) applied fuel load attribute values to initial and post-treatment stand conditions based on forest structure (Table 3.3). Potential behavior models included shrub fuel type models:

- Low-load, humid climate timber-shrub (SH4)
- High load, dry climate shrub (SH5)
- Low-load, humid climate shrub (SH6)

Timber-understory fuel type models:

- Low-load dry climate timber-grass-shrub (TU1)
- Very high load, dry climate timber-shrub (TU5)

Timber litter fuel type model:

- Moderate load conifer litter (TL3), and

Slash-blowdown fuel type models:

- Low-load activity fuel (SB1)
- Moderate load activity fuel or low load blowdown (SB2).

Depending of the size and density classes of the stand, fuel loadings in Mg ha^{-1} were assigned for 1-hour, 10-hour, and 100-hr fuels, as well as fuel bed depth in meters (Table 3.3). The fire behavior fuel models and fuel loadings were used as input parameters in the BehavePlus 5.0 fire modeling system (Andrews 2009, Andrews et al. 2008) to simulate fire behavior given the occurrence of wildfire under a specified set of moderate weather conditions (Table 3.4) and a slope steepness of 35%. Modeled fire behavior outputs from BehavePlus 5.0 were then used to generate "probability of fire-related mortality" look-up tables for the optimization model that covered the range of initial and post-treatment stand conditions (Table 3.5). This method makes no static assumptions about the effectiveness of low-thinnings for reducing wildfire severity and intensity, as it allows for BehavePlus to dynamically calculate fire behavior, given the occurrence, under moderate fire weather (Table 3.4) and the resultant post-treatment conditions.

Six of the eight fire behavior fuel models resulted in some type of fire mortality, depending on stand height and crown ratio. Two fuel models, TU1 and TU3 (Table 3.5) did not exhibit fire mortality given the occurrence of wildfire under the moderate weather conditions (Table 3.4). Similarly, the SB1 fire behavior fuel model only exhibited fire-related mortality at the lowest stand heights and highest crown ratios. The other five fuel models showed fire-related mortality up to 98%, with models SH5 and SH6 having the largest proportion of high stand mortality, and models SB2, SH4, and TU5 showing less mortality and more fluctuation in mortality levels as stand height increased and crown ratio decreased.

Fire effects on immediate fuel consumption or C emissions were set at 4.8% as determined from Campbell et al. (2007) for a large southwestern Oregon fire. The probability of fire occurrence within 10-year stages was modeled by a Poisson distribution (Eqn. 1) based on the mean fire return interval (mFRI) for each respective forest type determined by the LANDFIRE project spatial database (Hann et al. 2004, Schmidt et al. 2002):

$$P = \frac{\lambda t^{x}}{x!} e^{-\lambda t} \qquad (1)$$

Where:

	P	= probability that an event happens exactly x times in t successive years
	λ	= historical fires per year
	t	= stage length in years
	x	= no. of fire occurrences during stage

The three forest types fell into different probability of fire scenarios, depending on their mFRI. Fire occurrence probabilities were $P = 0.0244$, $P = 0.1100$, and $P = 0.3580$ for Mesic-wet Douglas-fir-western-hemlock (MWDF), Dry-Mesic Douglas-fir-western hemlock (DMDF), and Mediterranean California mixed conifer (MCME) forest types (Table 3.6).

3.3.5 Maximizing Terrestrial Carbon

Carbon in standing trees, both alive and dead, was calculated in the optimization model by way of allometric biomass equations to obtain the oven-dry mass of individual trees (Jenkins et al. 2003). For those trees harvested during treatment, aboveground biomass was calculated by the leaf, branch and top, stem bark, and stem wood components making up each tree. Carbon in the leaf, branch and top, and stem bark component pools was assumed to be immediately emitted. Carbon in stem wood was broken into long- and short-term storage by wood product and by-product category. Wood products in long-term storage were subject to an annual decay rate of 1%, while short-term storage was assumed to be an immediate emission. Carbon emissions due to the treatment of the stand and transportation of wood for processing were not included in the analysis because they are small in comparison to the potential carbon contributions of a forest over a 100-year period. Belowground carbon stocks were assumed to be constant, with tree ingrowth balancing treatment-generated stump and root decomposition.

A factor of 0.50 was applied to the oven-dry mass to determine the aboveground carbon content of forest stands at each state (Matthews 1993).

Furthermore, the potential carbon storage value is based on the over-the-counter (OTC) price suggested by Hamilton et al (2008). The objective function applied in the dynamic programming optimization algorithm of model was formulated by methods similar to those in Vanderberg et al. (2011), and is shown in Eqn. 2 below:

$$f_t(s, x_t) = x_t C[u_r u_d (1 - d_u L) + u_r (1 - u_d)] \qquad (2)$$

Where: $f_t(s, x_t)$ = carbon storage value due to decision x_t at stage t and state s

C = basal area to Mg C conversion

u_r = woody material utilization rate

u_d = fraction of utilized material subject to decay

d_u = decay rate for utilized woody material

L = decay horizon ($T - t$)

Rates for the parameters u_r, u_d, and d_u are shown in Table 3.6, as well as the monetary value of carbon stored in forests and wood products. T is equal to the overall planning horizon, which is 100 years, while t is equal to the length of time that has passed since the inception of the model run.

Dynamic programming used a backwards recursion method to determine the optimal management regime for each stand. The optimal management regime was the regime in which the decision at each stage maximized the carbon storage return over the 100-year planning horizon. At each stage t, the probability of events $F^*_{t+1}(x_t)$ and $F^*_{t+1}(x_{tfire})$ were used to calculate the expected value of the maximum carbon storage for stage t+1 given decision x_t (Eqn 3). Maximum terrestrial carbon returns from storage in the forest stand and wood products are then calculated as the recursion ends at stage 0. Optimal management regime pathways over time were then determined by a search algorithm within the model.

$$F_t^*(s) = \max_{x_t}\{ f_t(s, x_t) + [(1-P)F_{t+1}^*(x_t) + (P)F_{t+1}^*(x_{tfire})]\} \quad \text{for } t = 0,1,\ldots,T \tag{3}$$

Where:

$F_t^*(s)$	= maximum carbon storage for stage t and beyond, given state s at stage t
x_t	= decision variable that determines the destination state at stage t (ba per ha removed at the beginning of stage t)
$f_t(s, x_t)$	= carbon storage value due to decision x_t at stage t and state s
$F_{t+1}^*(x_t)$	= maximum carbon storage value for stage t+1, given decision x_t
$F_{t+1}^*(x_{tfire})$	= maximum carbon storage value for stage t+1, given decision x_t and the occurrence of fire
P	= probability of fire occurring during stage t+1

3.3.6 Simulation Time and Computing Resources

Table 3.7 shows solution times and number of decision states at the final stage for each sample of the three forest types. The model was run most often by a Dell OptiPlex system built with a 3.0 GHz dual-core processor and 4.0 GB of RAM. Other machines included a Dell Latitude laptop built with a 2.0 GHz dual-core processor and 1.0 GB of RAM, as well as a Dell Precision workstation built with 3.2 GHz quad-core processor and 6.0 GB of RAM. Solution times ranged from 16 minutes to approximately 16 hours depending on the machine and the initial stand parameter values. There was a noticeable difference in relative performance between computing resources.

3.4 RESULTS

3.4.1 Maximum Carbon Storage

Initial stand carbon, expected total accumulated carbon storage at the end of the planning horizon and expected 100-year gains for both optimal management regimes and control scenarios are shown in Table 3.8. Initial carbon conditions of the stands ranged from 70.26 to 358.38 Mg C ha^{-1}. Carbon accumulation rates for optimal regimes ranged from 2.99 to 5.50 Mg C ha^{-1} yr^{-1}, while rates for control scenarios ranged from 2.54 to 4.70 Mg C ha^{-1} yr^{-1}. Almost all stand samples had optimal solutions that included some frequency of low-thinning activity. However, the control solution was the optimal solution for the two stand samples MWDF2 and MWDF8.

Table 3.8 also shows the difference in expected carbon storage between control and optimal solutions, as well as the additional expected carbon storage of optimal treatment solutions as a percentage of the overall 100-year gain for control scenarios. Additional carbon is defined as the carbon gained by way of management activity compared to the grow-only control scenario. Excluding the two optimal control samples, the additional expected carbon storage by way of management activity compared to the control ranged from 21.22 to 170.31 Mg ha^{-1}. Similarly, the additional expected carbon storage of optimal solutions compared to the 100-year gain for control scenarios ranged from 7 to 43%.

3.4.2 Optimal Management Regimes

Treatment decisions for optimal management regimes are shown in Table 3.9. The intensity of thin-from-below treatments ranged from 0 to 15% of the standing basal area for sample stands. The optimal treatment frequency over the 100-year horizon increased from mesic-wet Douglas-fir-western hemlock to dry-mesic Douglas-fir western hemlock forests, and again from dry-mesic Douglas-fir western hemlock forests to Mediterranean California mixed evergreen forests. Treatment frequency also increased within forest types towards the middle of the planning horizon, while decreasing near the beginning and ends of the 100-year period.

3.4.3 Visualization of Optimal Solution vs. Control

One of the best-performing stands in terms of maximizing expected forest carbon and carbon in wood products was sample 9 of the dry-mesic Douglas-fir-western hemlock forest type. The optimal management regime was to remove 15% of the basal area by thinning-from-below in years 20 through 40, then let the stand grow until year 60 where the decision was made to remove 15% of the basal area and let the stand grow until the end of the planning horizon. Figures 3.2 – 3.12 depict the 100-year optimal management regime, diameter and height distributions for the stand and compares them to the grow-only control scenario. It should be noted that the figures show the initial conditions of the stand at the beginning of the representative stage, therefore treatment decisions are not visible until the following stage representation (e.g., the removal at year 20 is visible at year 30).

3.5 DISCUSSION

3.5.1 Optimal Carbon Management

Management regimes can maximize expected carbon storage by regulating the influence of thinning-from-below treatments and the removal and utilization of treatment-generated woody material to keep the risk of fire-related mortality and subsequent carbon losses at low levels. Our model chose at least one low-thinning of 15% of the basal area for 93% of the 30 stand samples from the three forest types. The frequency and intensity of treatments across forest types for optimal solutions suggest that management for the risk of fire-related carbon losses becomes more important as initial stand density increases and mFRI and average tree size decrease. Also, the optimal expected carbon storage gains within the planning horizon as well as the additional expected carbon storage of optimal solutions compared to the 100-year gain for control scenarios, increased with initial stand density and decreased with mFRI and average tree size. These observations suggest that if maximizing terrestrial carbon contributions from forests with similar initial conditions to those in this study is the objective, then management resources should be allocated to stands within the Mediterranean California mixed evergreen, dry-mesic Douglas-fir-western hemlock, and mesic-wet Douglas-fir-western hemlock forest types in that order.

Creation of forest stands more resilient to disturbance events can lead to additional forest-based terrestrial carbon storage. As seen in Figures 3.2 – 3.12, both the control and the optimal management regime move towards lower stand densities, larger trees, and higher canopy base heights, but the main difference between the two regimes is that the optimal decision strategy creates a more fire-resilient structure at an earlier time within the planning horizon. The utilization of treatment-generated woody material, coupled with the increased growth rate and lower fire-related mortality rate leads towards a greater overall expected carbon storage by minimizing the risk of catastrophic loss due to wildfire and providing the ability to somewhat control the end use of removals destined to become wood products.

The value of the additional expected carbon storage of optimal solutions compared to the 100-year gain for control scenarios can be calculated if a current market price for carbon is applied. Optimal treatment regimes could store more terrestrial carbon than control solutions with values ranging from $145 to $990 per hectare.

3.5.2 Strategic Planning vs. Buffer Pool Risk Management

Planning with carbon buffer pools to compensate with risk associated with disturbance can require the size of the buffer deposit to range from 10 to 60% of the generated carbon credits, depending on the risk class determined for a given project (VCS 2008). The results from the optimization model, which incorporates a risk of loss due to wildfire over time for the forest types and initial stand conditions in this study, show that the expected carbon storage of optimal solutions compared to the 100-year gain for control scenarios ranged from 8 to 46%, which rival buffer pool risk management strategies. Making decisions with incorporated disturbance and risk of loss by mathematical expected value, as with the optimization model, can lead to additional carbon storage values that rival the required buffer pool deposits by the

Voluntary Carbon Storage hedge method of risk management. This presents the question of how might management planning with the inclusion of risk into the decision making process be different compared to the VCS method of merely accounting for risk via reserve pooling (i.e., managing for risk of loss to store more carbon than expecting losses and keeping reserves to cover losses). Currently, the hedge method acts as a penalty to landowners participating in forest carbon offset projects, with long-term management strategies accounting for risk outside of the planning process. Not only does this penalize landowners in the short-term by delaying a portion of payments for additionally-stored carbon, it also decreases the potential for maximizing forest and wood-product carbon storage over the project period, resulting in sub-optimal return both economic and environmental investments. Future work in this area might be well-served by empirically comparing the two risk management strategies.

3.5.3 Model Limitations

This study only focuses on a subset of western Oregon forest types, and although mean fire return intervals are determined from the published biophysical settings for each forest type, they are constant within forest types and the planning horizon. A more robust approach could be accomplished by the use of stochastic determination of fire occurrence probabilities. That approach was not used in this study due to much greater solution times and the increased computing power needed to apply the analysis within the current model framework.

The assumptions for the utilization of treatment-generated woody material were also based upon published values, although it would be naïve to concur that the solutions provided by the optimization model would not differ if utilization values were manipulated (Table 3.6). Preliminary sensitivity analyses show decreasing optimal returns in carbon storage as the treatment-generated woody material utilization rate is lowered to 40% of removal volume, but display a similar pattern in management frequency and intensity. However, elevated decay rates for fire-killed trees, dead biomass, and long-lived wood products show a shift towards no management activity, especially in the mesic-wet Douglas-fir-western hemlock forest type, which has a mean fire return interval of 400 years.

The nature of these parameters lend themselves to manipulation by users concerned about a particular forest stand with a certain set of locally-defined utilization parameter values based on harvest practices and available wood product markets. The conditions for fire spread were also held constant, and can be expected that changes in these conditions will also impact the optimal determination of management regimes. The use of optimization model can be used to determine optimal management regimes for maximizing the expected value of carbon storage within the 3 forest types regardless of initial stand conditions, utilization parameters, and weather conditions based on unique scenarios.

The optimization model also depends on the empirically-derived individual-tree growth and mortality equations, as well as aboveground biomass equations that have been restricted to Douglas-fir. Since fire-related mortality is a function of canopy base height, and hardwoods exhibit slower height growth and also lower crown base heights, this method was used to provide a conservative approach to fire-related mortality in mixed-conifer forests with a hardwood component. Further research with the model could incorporate species-specific growth and mortality equations for both conifer and hardwood trees.

The carbon values calculated by the model are slightly high compared to the work of Smithwick et al. (2002), in terms of annual accumulation rate and average overall storage potential. This could be due in part to the high utilization level for treatment-generated woody biomass (80%), as explained earlier. However, the model outputs are consistent with the values suggested by Nabuurs and Mohren (1995) who report annual C accumulation values of 2.93 to 4.17 Mg C ha^{-1} yr^{-1} over a 100-year rotation. Furthermore, the treatment of stands also decreases its susceptibility to wildfire, whether it be high-severity or low-severity, and thus avoids the immediate pyrogenic emissions as well as the biogenic emissions from fire-killed trees over time.

Finally, the model employs levels of low thinnings as the silvicultural treatment, exclusively, and at discrete time intervals of 10-years. This method was chosen because low-thinning treatments target trees from the smallest diameter class first until the target residual basal area is met, and is therefore used as a proxy for creating stand structures that favor larger trees and lower stand densities. Thinning-from-below was also chosen based on the work of Mitchell et al. (2009), who suggest that understory removal is the only type of treatment capable of simultaneously reducing fire severity and potentially increasing carbon storage. Our research suggests that only two of the stand samples, both of which were selected from the mesic-wet Douglas-fir western hemlock forest type, exhibited control scenarios as the optimal regime for storing carbon. However, our study utilizes treatment decisions at 10-year intervals, and our results coincide well with recent work from Cathcart et al. (2010) and Hurteau and North (2010). Cathcart et al. (2010) reports that potential carbon returns can breakeven 9-years post-treatment in a south-central Oregon watershed, while Hurteau and North (2010) report negative net carbon stocks initially in post-treatment mixed-conifer stands with recovery and net carbon gains after 7 years. Our results suggest that stands can generate positive net carbon stocks within 10 years, at strategically-timed intervals, when also utilizing treatment-generated woody biomass for long-lived wood products.

3.6 CONCLUSION

Maximizing carbon storage in fire-prone western Oregon forests can be accomplished through the strategic timing of low thinning-type silvicultural treatments that manipulate stand structure and decrease the risk of fire-related mortality. The optimization model employed in this paper suggests that, under the specified conditions (Table 3.4) strategically-timed low-thinning treatments of up to 15% in stand basal area reduction can increase carbon storage up to 46% compared to no-treatment, grow-only control scenarios in three western Oregon forest types of 40 to 120 years in age with initial densities 182 to 2441 trees per hectare and mean fire return intervals from 8 to 400 years (Table 3.2, Table 3.7).

The results of this study suggest that management regimes that maximize the expected carbon storage for the sample stands within the forest types in this study can benefit from the influence of thinning-from-below and the removal and utilization of treatment-generated woody material to keep the risk of fire-related mortality and subsequent carbon losses at low levels. The results of this study also suggest that creation of forest stands more resilient to disturbance events could be beneficial to carbon storage, and create carbon stores with market values ranging from $145 to $990 per hectare. In regards to the current Voluntary Carbon Standard method of risk management, making decisions with the model can lead to additional carbon storage values that rival the required buffer pool deposits by the hedge method of risk management.

The optimization model is applicable to wide range of initial stand conditions, potential silvicultural treatments, and fire-related weather conditions for fire-prone western Oregon forests. The model may be used to determine optimal management regimes for forest stands, but decisions are restricted to the management unit and does not consider the impact of surrounding stands. The scaling-up of the optimization model may be of use in determining optimal management regimes for planning purposes at the landscape level.

3.7 REFERENCES

Andrews, P.L. 2009. BehavePlus fire modeling system, version 5.0: Variables. Gen. Tech. Rep. RMRS-GTR-213WWW Revised. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 111 p.

Andrews, P.L., C.D. Bevins, and R.C. Seli. 2008. BehavePlus fire modeling system, version 4.0: User's guide. Gen. Tech. Rep. RMRS-GTR-106WWW Revised. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station. 116 p.

Arno, S.F. and C.E. Fiedler. 2005. Mimicking Nature's Fire: Restoring Fire-Prone Forests in the West. Island Press, Washington, DC.

Birdsey, R., Pregitzer, K., Lucier, A. 2006. Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality 35: 4197-4202.

Campbell, J., D. Danato, D. Azuma, and B. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, United States. Journal of Geophysical Research 112, G04014, doi: 10.1029/2007JG000451.

Cathcart, J., A.A. Ager, A. McMahon, M. Finney, and B. Watt. 2010. Carbon benefits from fuel treatments. In: Jain, T.B.; Graham, R.T.; and Sandquist, J., tech. eds. 2010. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate: Proceedings of the 2009 National Silviculture Workshop, Boise, ID. RMRS-P-61. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 351 p.

Chen, J., S.J. Columbo, M.T. Ter-Mikaelian, and L.S. Heath. 2010. Carbon budget of Ontario's managed forests and harvested wood products, 2001-2100. Forest Ecology and Management 259: 1385-1398.

Curtis, R.O., G.W. Clendenen, and D.J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. Gen. Tech. Rep. PNW-128. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Research Station. 79 p.

Curtis, R.O. 1994. Some simulation estimates of mean annual increment of Douglas-fir: Results, limitations, and implications for management. Research Paper PNW-RP-471. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 33 p.

Davis, S.C., A.E. Hessl, C.J. Scott, M.B. Adams, and R.B. Thomas. 2009. Forest carbon sequestration changes in response to timber harvest. Forest Ecology and Management 258: 2101-2109.

Gill, S.J., G.S. Biging, and E.C. Murphy. 2000. Modeling conifer tree crown radius and estimating canopy cover. Forest Ecology and Management 126: 405-416.

Graetz, D. and P. Bettinger. 2005. Determining thinning regimes to reach stand density targets for any-aged stand management in the Blue Mountains of eastern Oregon. In: Bevers, M.; Barrett, T.M., comps. 2005. Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium. Gen. Tech. Rep. PNW-GTR-656. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 10 p.

Hamilton, K., M. Sjardin, T. Marcello, and G. Xu. 2008. Forging a frontier: state of voluntary carbon markets 2008. A report by Ecosystem Marketplace and New Carbon Finance. Forest Trends Association, Washington, D.C.

Hann, W., A. Shilsky, D. Havlina, K. Schon, S. Barrett, T. DeMeo, K. Pohl, J. Menakis, D. Hamilton, J. Jones, M. Levesque, and C. Frame. 2004. Interagency fire regime condition class guidebook. Last update January 2008: Version 1.3.0 [Homepage of the Interagency and The Nature Conservancy fire regime condition class wevsite, USDA Forest Service, US Department of the Interior, The Nature Conservancy, and Systems for Environmental Management]. [Online]. Available: www.frcc.gov.

Hann, D.W. and C.H. Wang. 1990. Mortality equations for individual trees in southwest Oregon. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. Research Bulletin 67. 17p.

Hann, D.W. and D.R. Larsen. 1991. Diameter growth equations for fourteen tree species in southwest Oregon. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. Research Bulletin 69. 18p.

Hurteau, M.D. and M. North. 2010. Carbon recovery rates following different wildfire risk mitigation treatments. Forest Ecology and Management 260: 930-937.

Hurteau, M.D., B.A. Hungate, and G.W. Koch. 2009. Accounting for risk in valuing forest carbon offsets. Carbon Balance and Management 4(1): 14p. doi:10.1186/1750-0680-4-1

Hurteau, M. and M. North. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modelled wildfire scenarios. Frontiers in Ecology and the Environment 7: 6p. doi:10.1890/080049

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, R.A. Birdsey. 2003. National-scale biomass estimators for United States tree species. Forest Science 49(1): 12-35.

Matthews, G. 1993. The carbon content of trees. In: Forestry Commission Technical Paper 4, Edinburgh, UK: Forestry Commission.

Mitchell, S.R., M.E. Harmon, and K.E.B. O'Connell. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19(3): 642-655.

Nabuurs, G.J. and G.M.J Mohren. 1995. Modelling analysis of potential carbon sequestration in selected forest types. Canadian Journal of Forest Research 25(7): 1157-1172.

North, M., M. Hurteau, and J. Innes. 2009. Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. Ecological Applications 19(6): 1385-1396.

Nunery, J.S. and W.S. Keeton. Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products. Forest Ecology and Management 259: 1363-1375.

Reinhardt, E. and L. Holsinger. 2010. Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky Mountains. Forest Ecology and Management 259: 1427-1435.

Ritchie, M.W. and D.W. Hann. 1990. Equations for predicting height growth of six conifer species in southwest Oregon. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. Research Paper 54. 12p.

Ruddell, S., R. Sampson, M. Smith, R. Giffen, J. Cathcart, J. Hagan, D. Sosland, J. Godbee, J. Heissenbuttel, S. Lovett, J. Helms, W. Price, and R. Simpson. 2007. The role for sustainably managed forest in climate change mitigation. Journal of Forestry 105(6): 314-319.

Schmidt, K.M., J.P. Menakis, C.C. Hardy, W.J. Hann, and D.L. Bunnell. 2002. Development of course-scale spatial data for wiland fire and fuel management. Gen. Tech. Rep. RMRS-GTR-87. Fort Collins, CO. USDA Forest Service, Rocky Mountain Research Station. 41 p.

Scott, J.H. and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO. USDA Forest Service, Rocky Mountain Research Station. 72 p.

Smithwick, E.A.H., M.E. Harmon, S.M. Remillard, S.A. Acker, and J.F. Franklin. 2002. Potential upper boundsof carbon storage in forest of the Pacific Northwest. Ecological Applications 12(5): 1303-1317.

Solomon, A., R. Birdsey, L. Joyce, and J. Hayes. 2009. Forest service global change research strategy, 2009-2019. USDA Forest Service Research and Development FS-917a. Washington D.C. 20 p.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forest of western Oregon and Washington. Ecology 69(6): 1689-1702.

Vanderberg, M.R., K. Boston, and J. Bailey. 2011. Maximizing carbon storage in the Appalachians: a method for considering the risk of disturbance events. IN: Proceedings of the 17th Central Hardwood Forest Conference. Lexington, KY. April 5-7. U.S. Department of Agriculture, Forest Service, Gen. Tech. Rep.

VCS. 2008. Voluntary Carbon Standard: Tool for AFOLU Non-Permanence Risk Analysis and Buffer Determination. 16 p. www.v-c-s.org

Winjum, J.K., S. Brown, and B. Schlamadinger. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. Forest Science 44(2): 272-284.

Ximenes, F.A., W.D. Gardner, and A.L. Cowie. 2008. The decomposition of wood products in landfills in Sydney, Australia. Waste Management *In Press* doi:10.1016/j.wasman.2007.11.006

Zumrawi, A.A. and D.W. Hann. 1989. Height to crown base equations for six tree species in the central western Willamette Valley of Oregon. Oregon State University, Forest Research Laboratory, Research Paper 52. 9p.

Zumrawi, A.A. and D.W. Hann. 1993. Diameter growth equations for Douglas-fir and grand fir in the western Willamette Valley of Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Contribution 4. 6p.

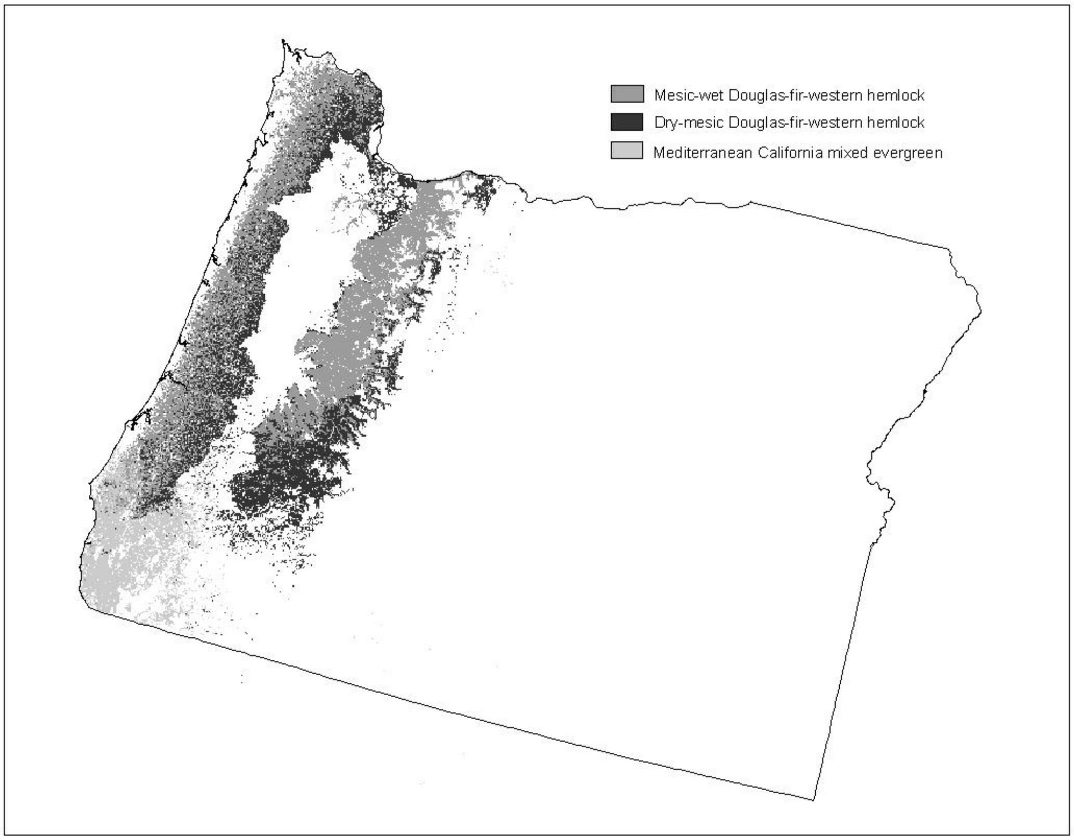

Figure 3.1 – Geographic areas of sampled Douglas-fir-dominated forest types in western Oregon

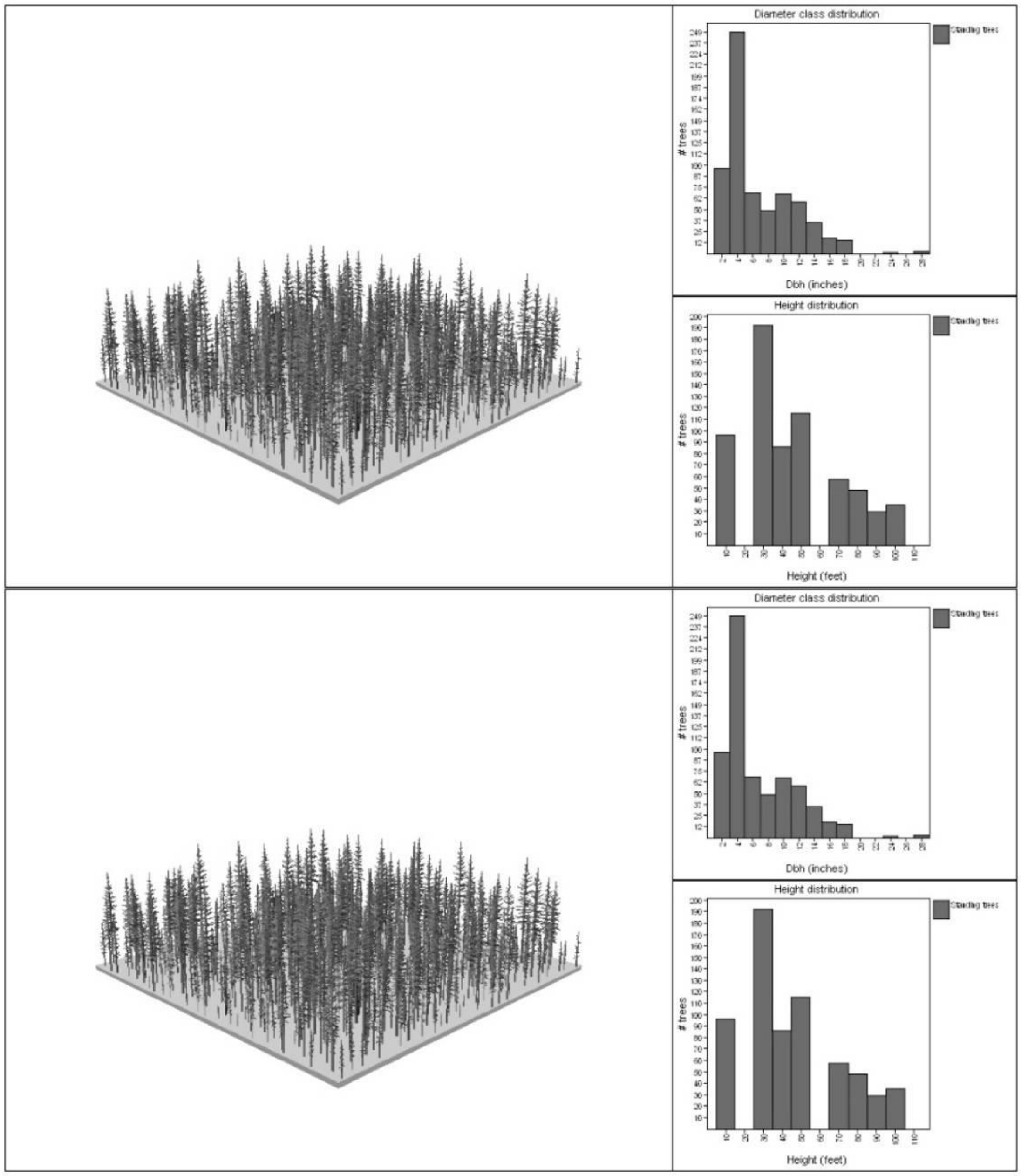

Figure 3.2 – SVS representation of initial stage (year 0) stand structure for DMDF9 {optimal (top) vs. control (bottom)}

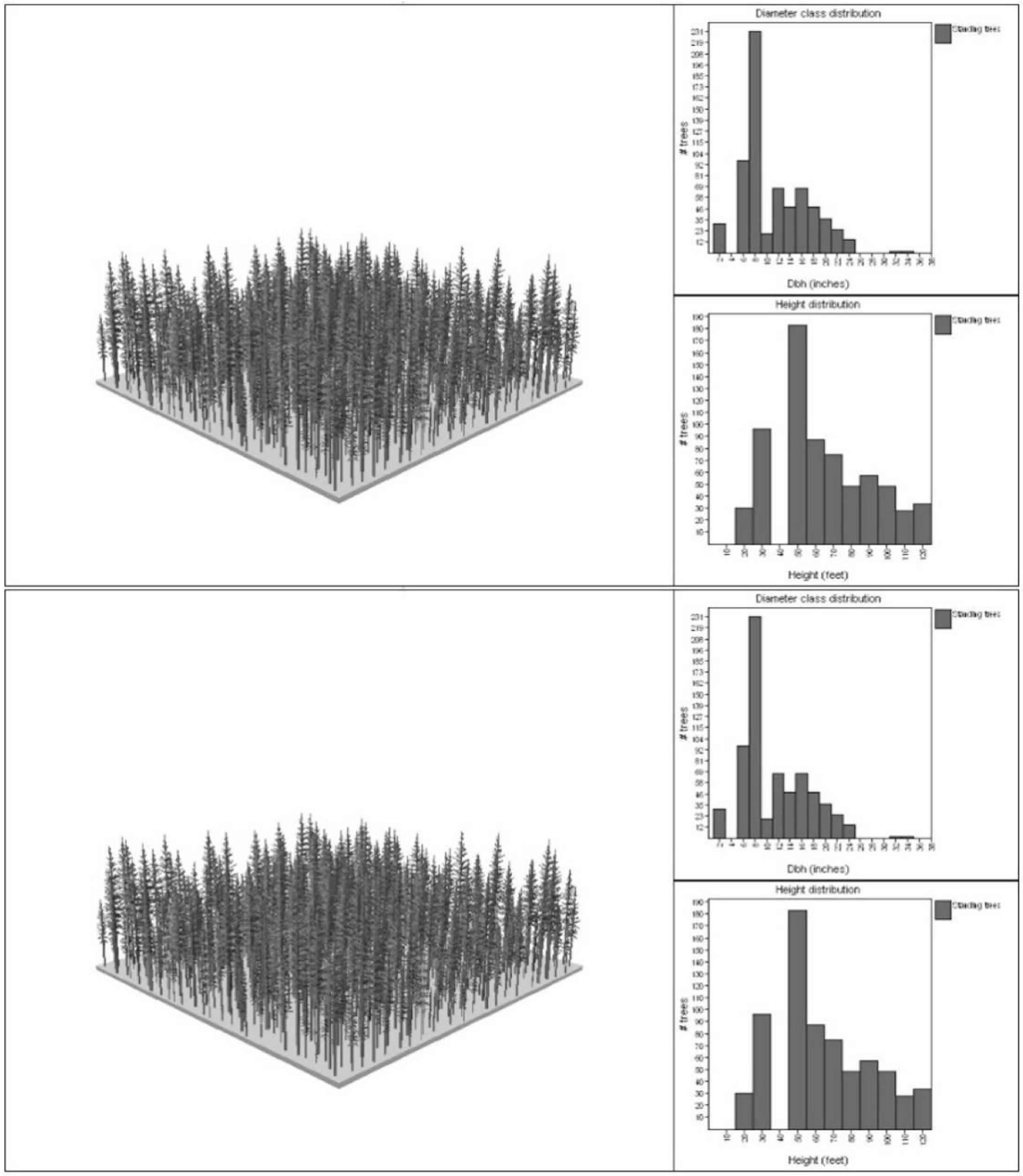

Figure 3.3 – Year 10 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

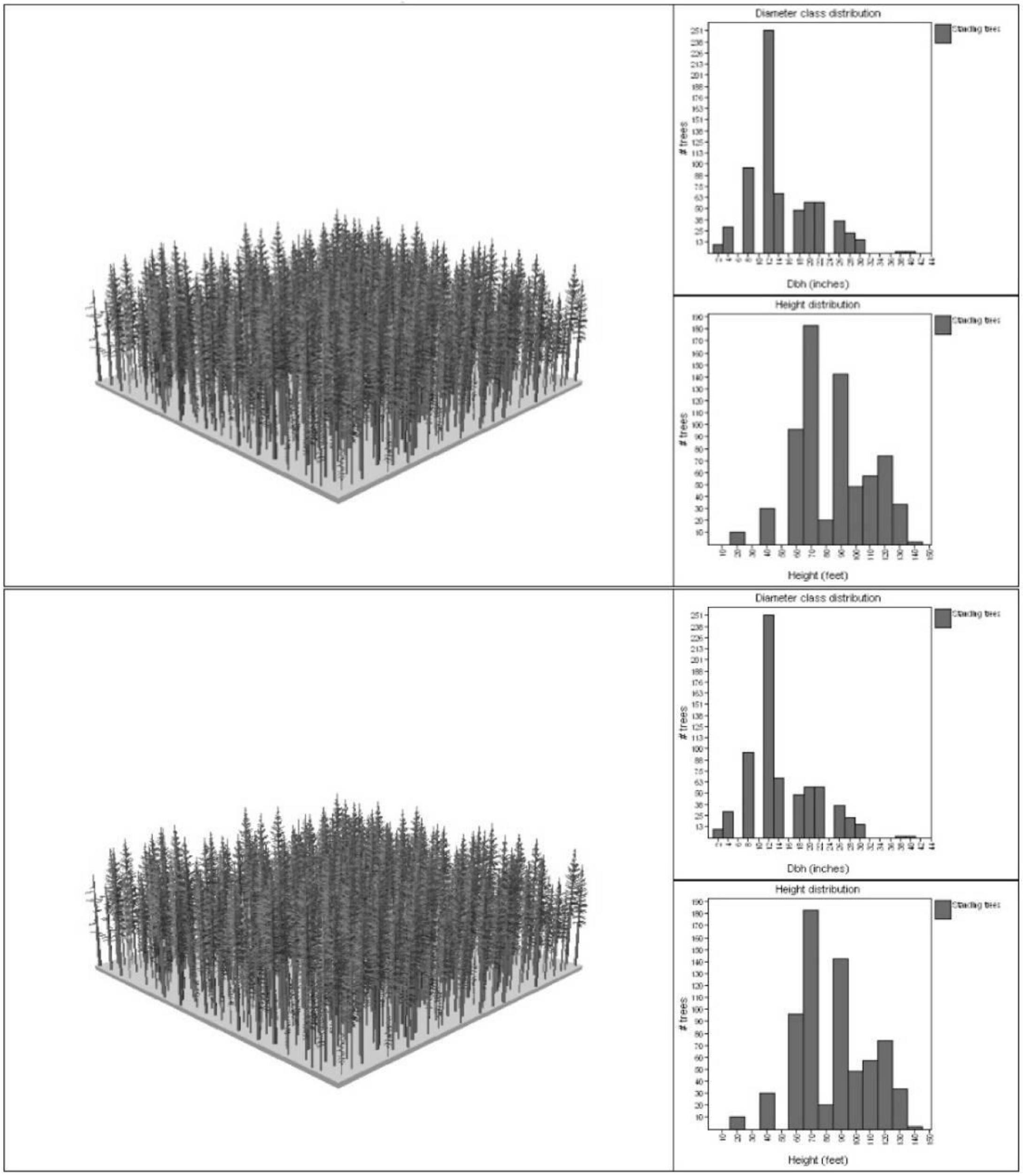

Figure 3.4 – Year 20 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

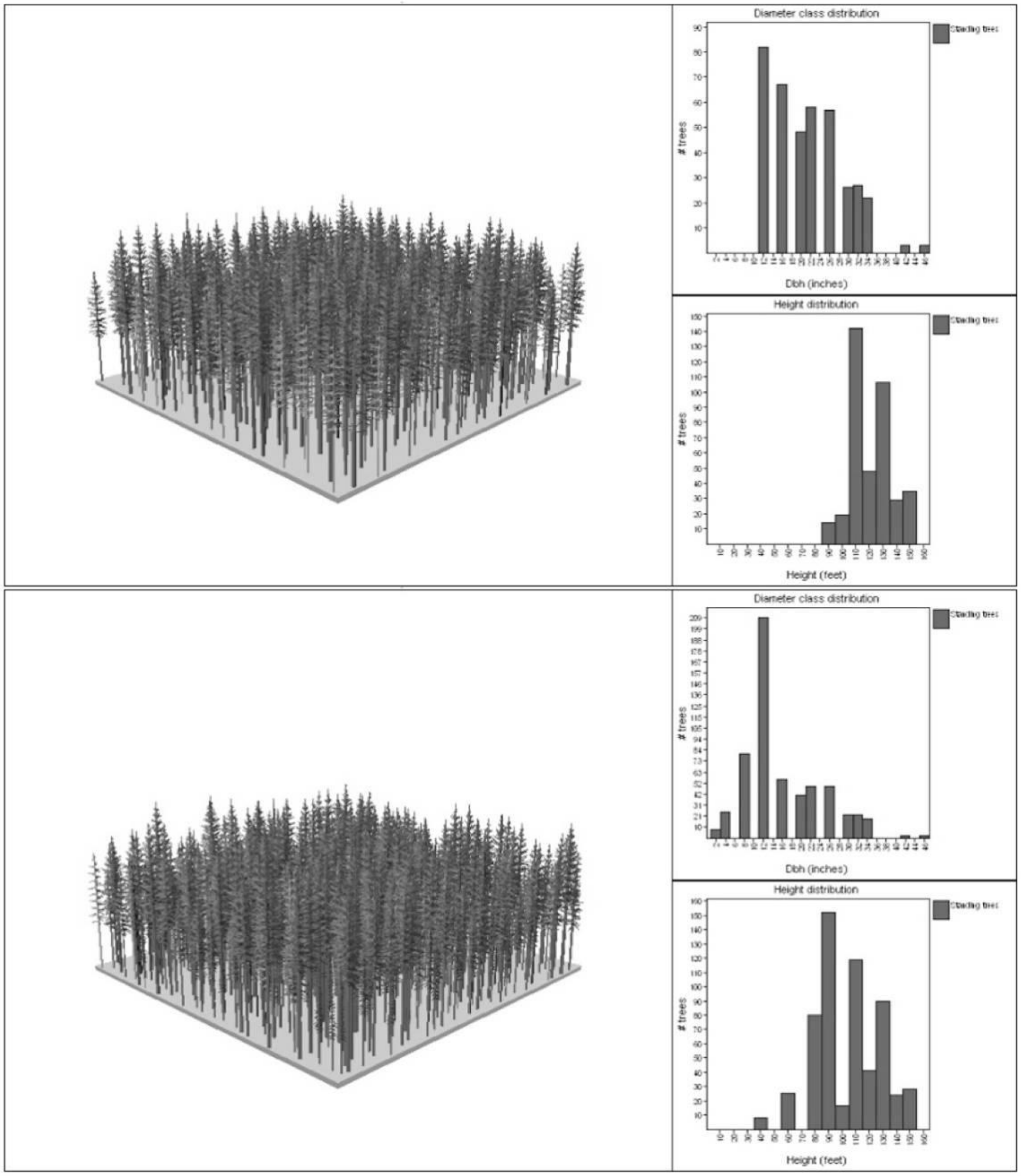

Figure 3.5 – Year 30 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

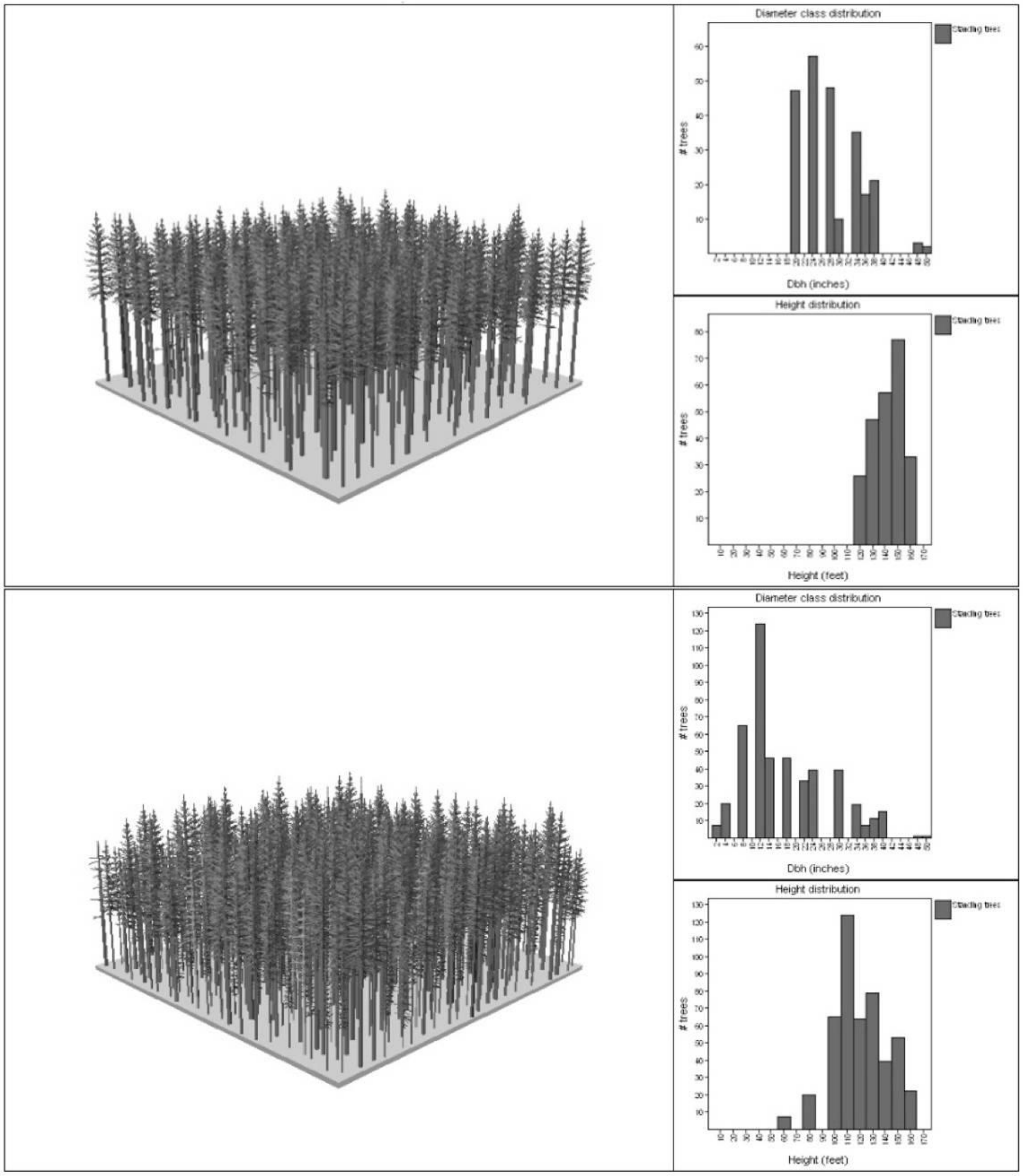

Figure 3.6 – Year 40 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

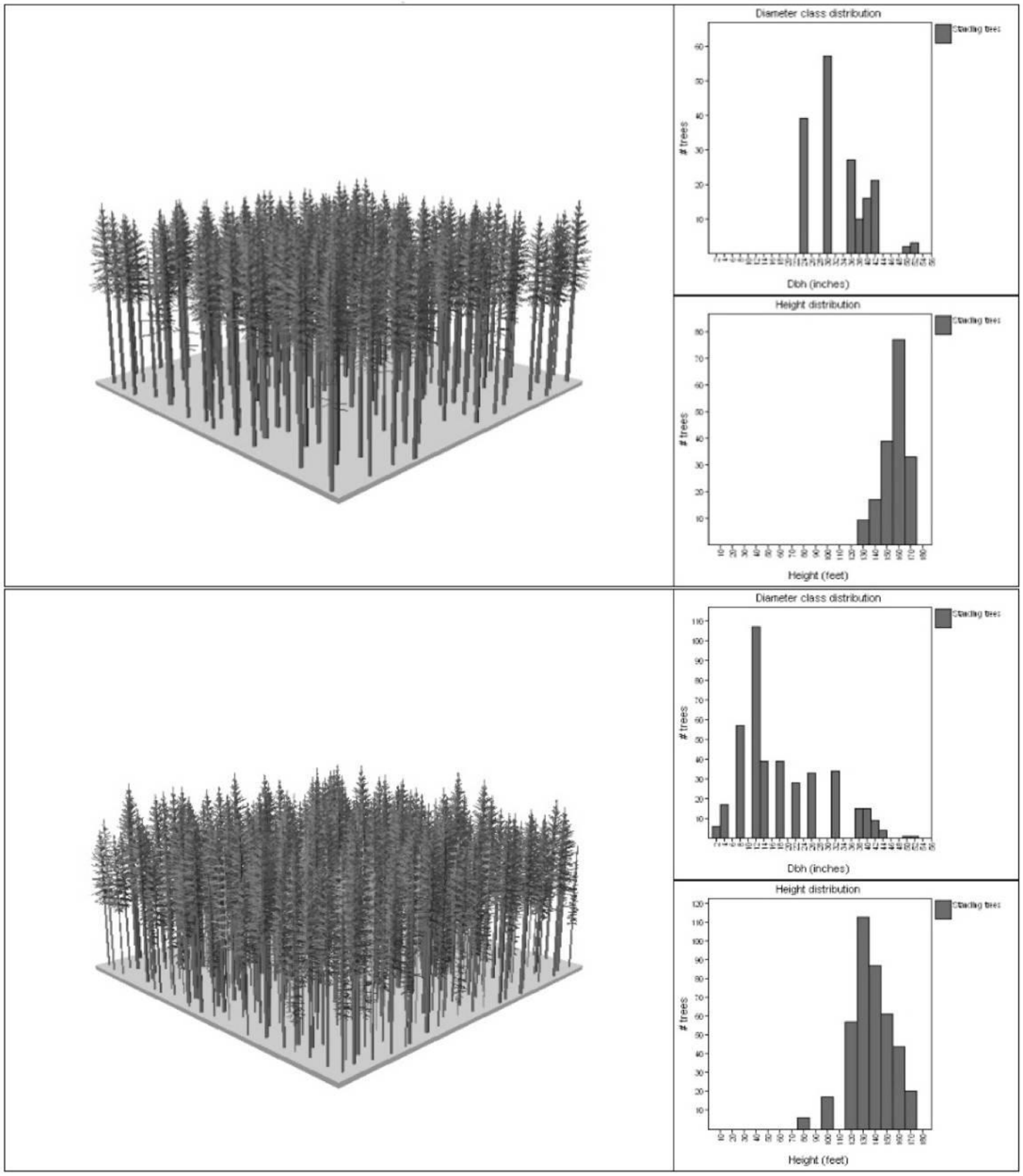

Figure 3.7 – Year 50 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

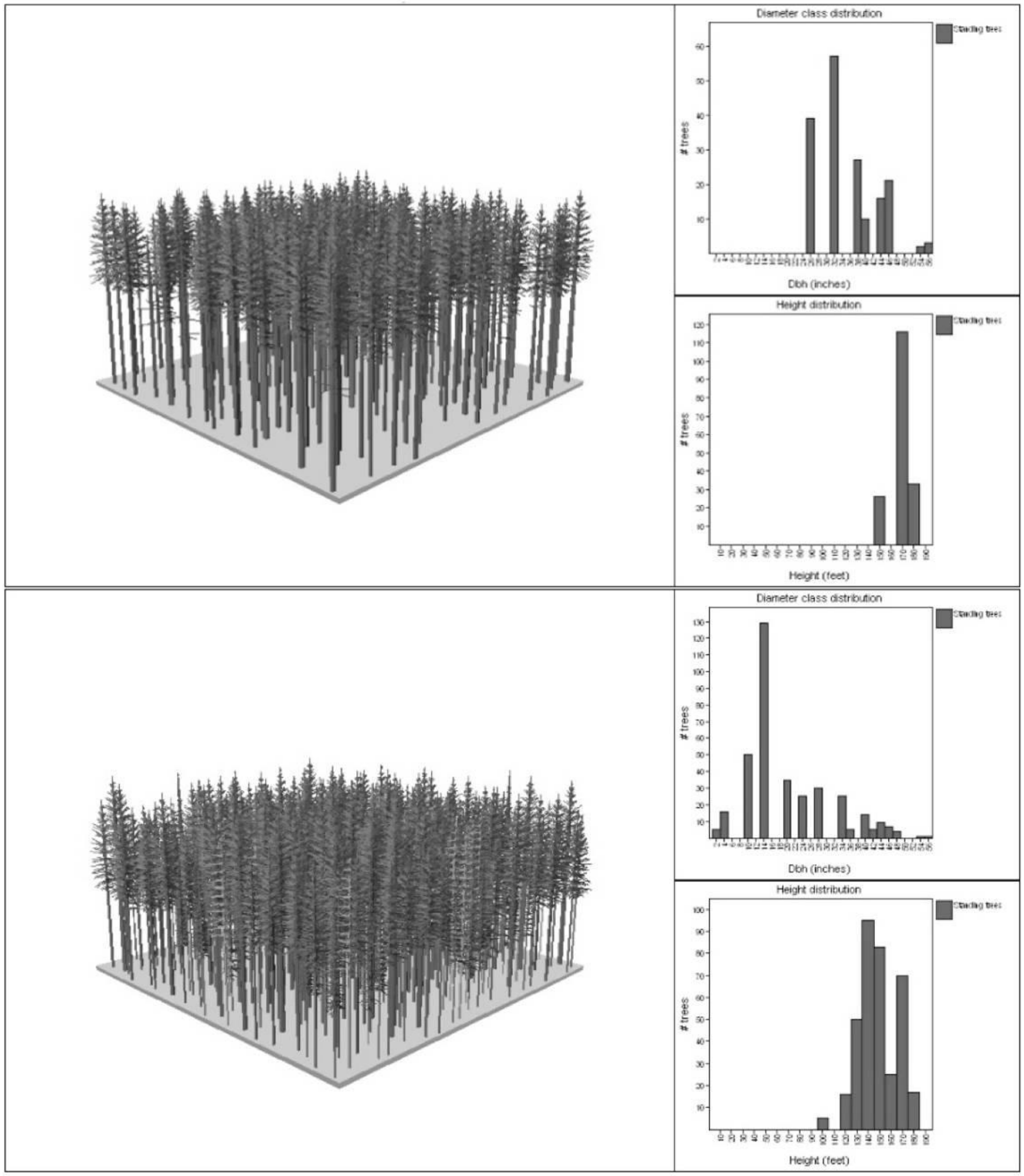

Figure 3.8 – Year 60 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

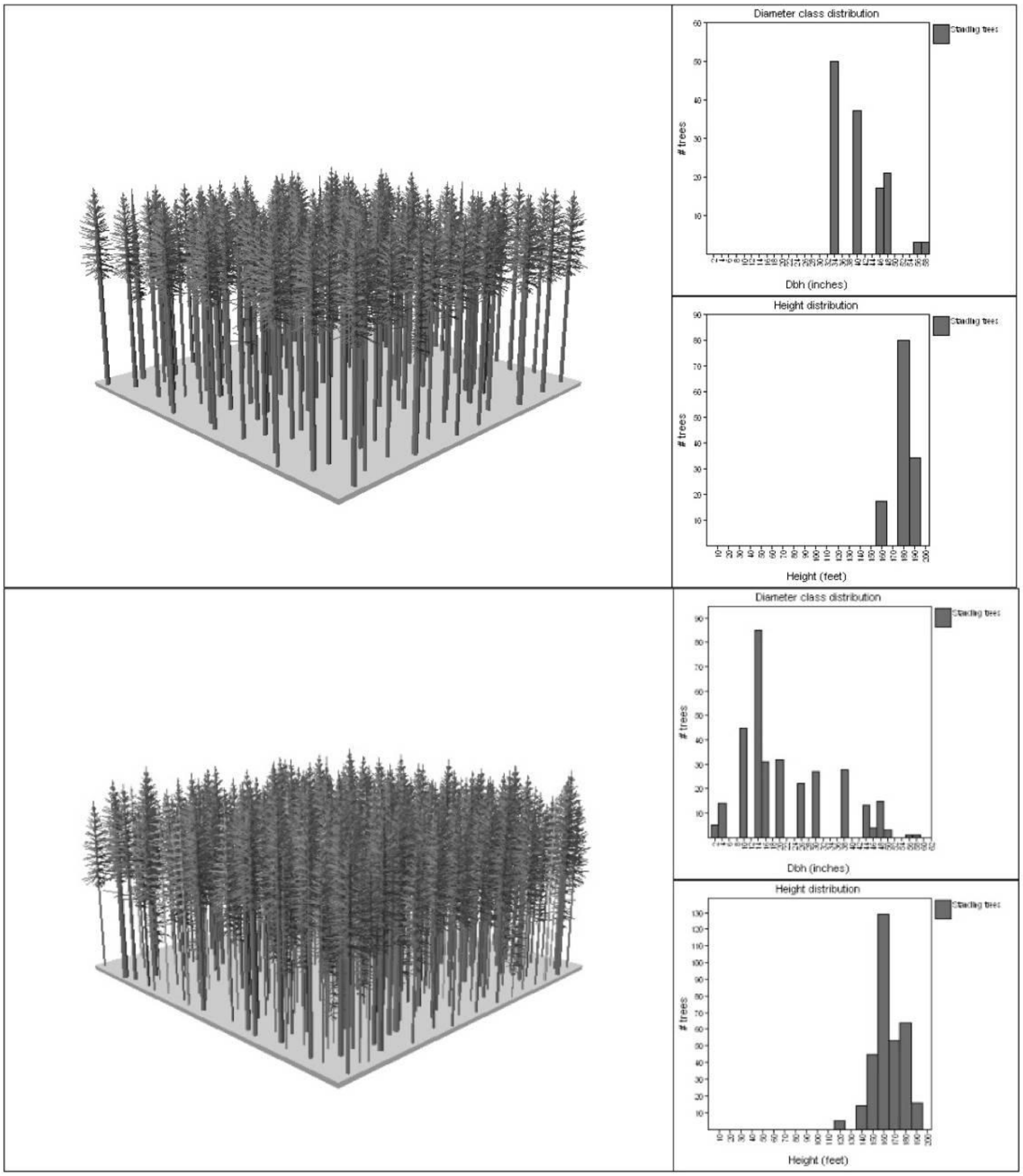

Figure 3.9 – Year 70 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

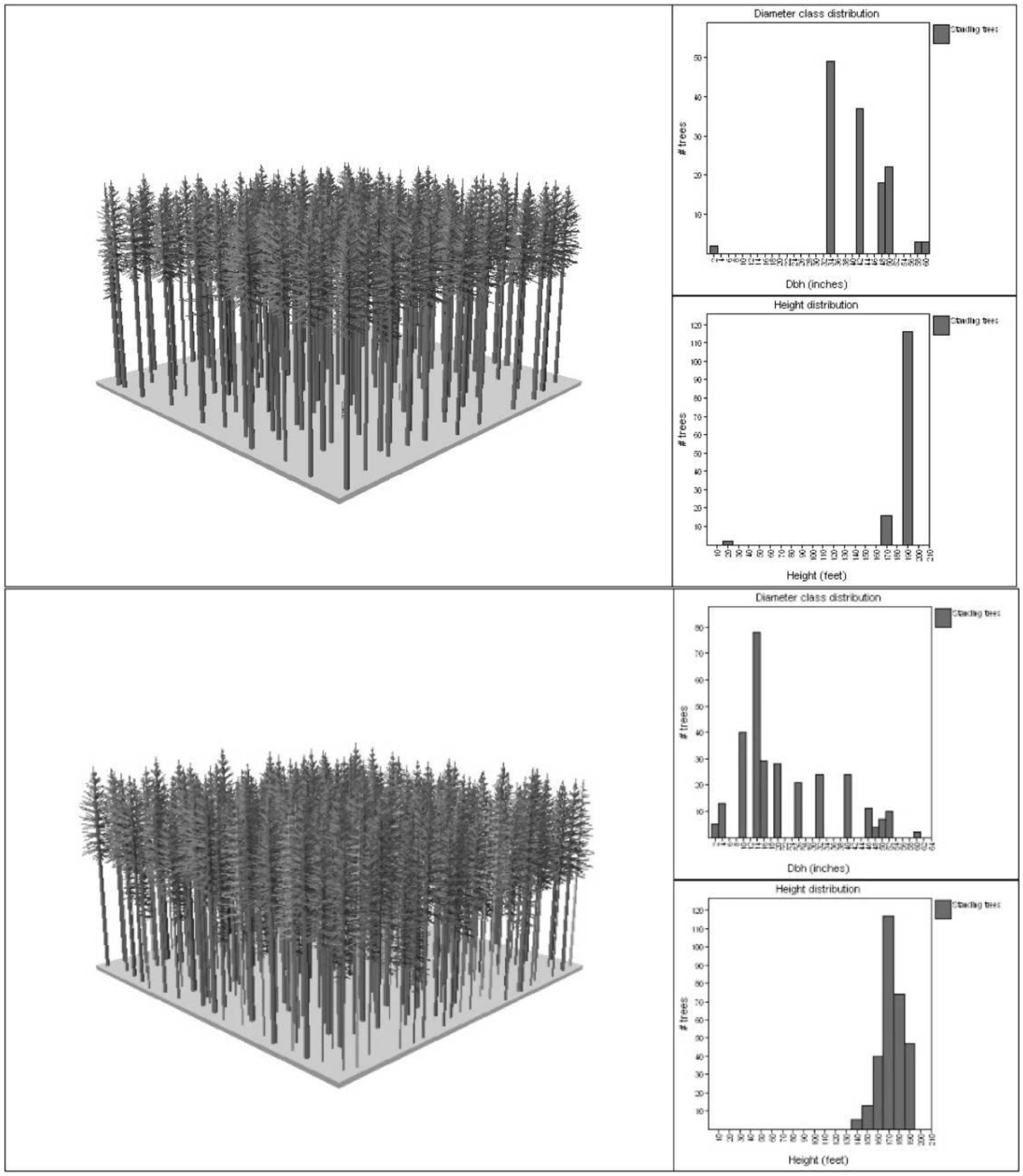

Figure 3.10 – Year 80 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

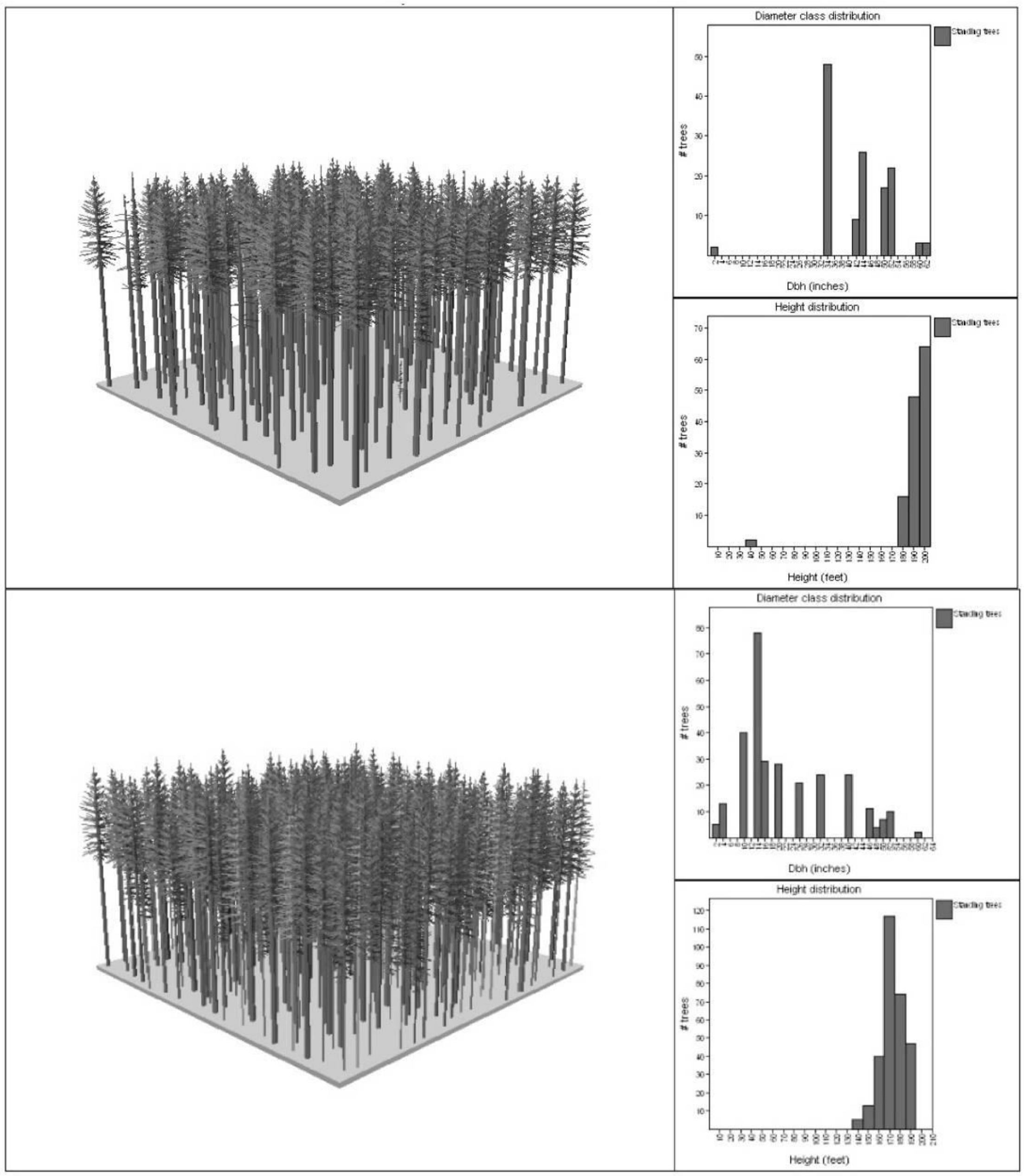

Figure 3.11 – Year 90 SVS representation of solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

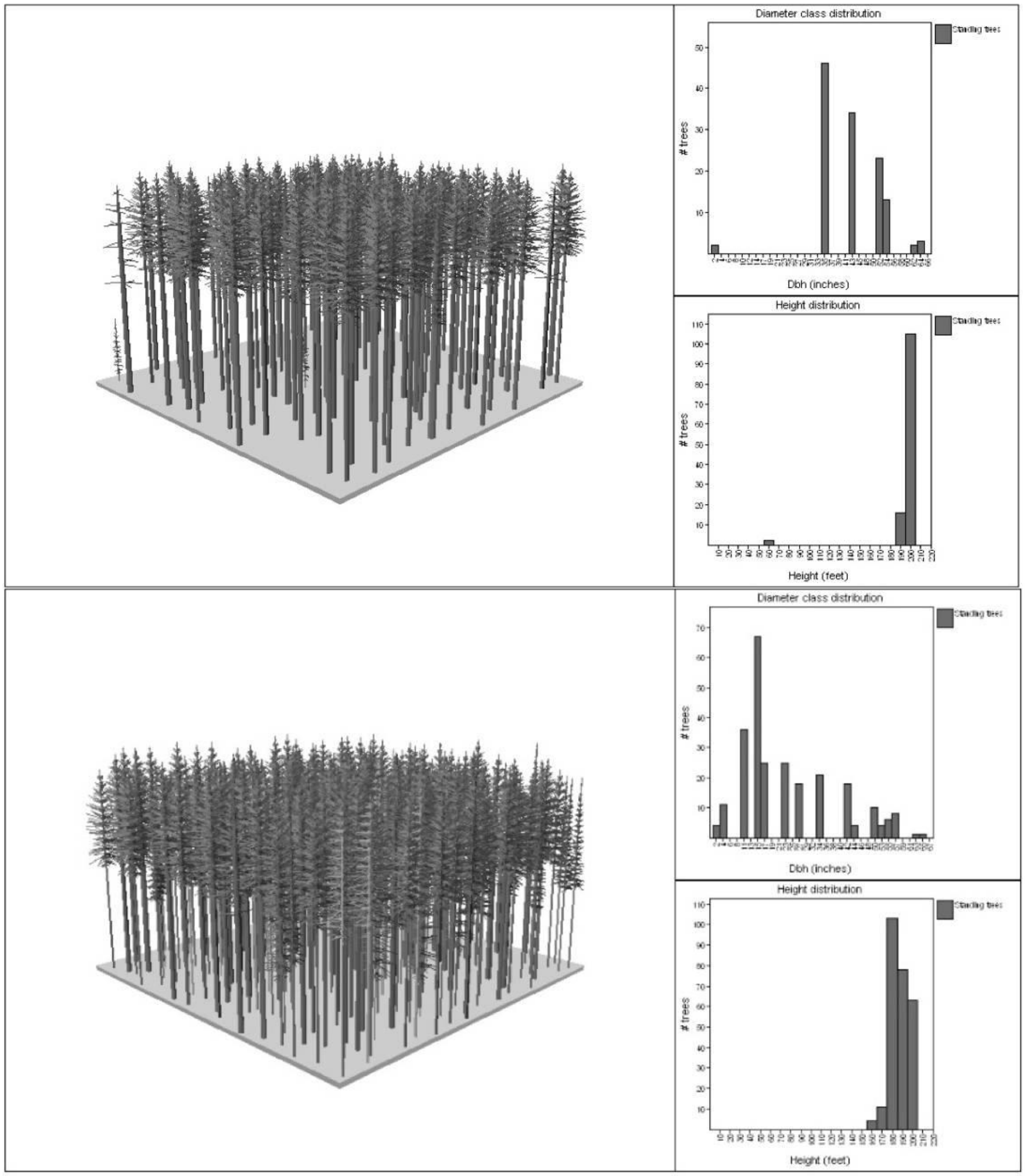

Figure 3.12 – SVS representation of final stage (year 100) solution stand structure for sample DMDF9 {optimal (top) vs. control (bottom)}

Table 3.1 – Characteristics of forest types used for carbon management optimization

Forest type	Fire interval	Fire severity	Dominant species	Geography	FFE-FVS variant
Mesic-wet Douglas-fir-western hemlock	400 years	99% replacement	*Psuedotsuga menziesii* *Tsuga heterophylla* *Thuja plicata*	Cascade Range (north slopes), Coast Range (western)	Pacific Northwest & Western Cascades
Dry-mesic Douglas-fir-western hemlock	80 years	24% replacement 76% mixed	*Psuedotsuga menziesii* *Tsuga heterophylla* *Thuja plicata* *Alnus rubra*	Willamette Valley (upper foothills), Coast Range (eastern), Cascades (western)	Pacific Northwest & Western Cascades
Mediterranean California mixed evergreen	8 years	2% replacement 22% mixed 76% surface	*Psuedotsuga menziesii* *Lithocarpus densiflorus* *Arbutus menziesii* *Quercus chrysolepis*	Klamath-Siskiyou Mountains	Inland California & Southern Cascades

Table 3.2 – Sample stand characteristics for each forest type

Forest type	Sample no.	Age (yrs)	QMD (cm)	Trees ha^{-1}	Basal area (m^2 ha^{-1})	Site index
Mesic-wet Douglas-fir-western hemlock	0	90	58.23	374	58.08	107
	1	100	70.93	192	60.52	127
	2	110	76.96	70	29.36	114
	3	110	63.49	226	62.93	122
	4	110	69.42	445	63.43	124
	5	100	75.37	274	56.98	116
	6	110	78.99	182	71.09	124
	7	110	62.01	538	47.82	123
	8	110	93.83	139	54.45	104
	9	70	50.05	245	43.36	130
Dry-mesic Douglas-fir-western hemlock	0	90	37.59	410	26.69	79
	1	70	37.79	596	35.45	84
	2	80	36.99	658	38.95	68
	3	100	48.49	894	59.88	103
	4	40	29.47	641	28.39	106
	5	100	51.99	585	73.37	146
	6	110	67.19	190	62.95	110
	7	90	44.47	513	50.25	94
	8	100	51.57	258	44.62	137
	9	90	28.58	678	22.76	112
Mediterranean California mixed evergreen	0	70	37.51	906	59.61	130
	1	110	44.81	892	29.8	90
	2	90	34.65	785	41.26	100
	3	80	35.22	1193	41.32	91
	4	90	46.57	1205	31.04	94
	5	100	32.87	2441	58.7	98
	6	80	25.49	1781	35.07	71
	7	90	37.95	1219	19.02	73
	8	120	36.79	758	35.27	83
	9	70	34.57	642	22.81	80

Table 3.3 – Fire behavior fuel model (FBFM) selection matrix

Size class	**< 4 cm**	**4 - 13 cm**				**13 - 23 cm**				**23 - 53 cm**				**> 53 cm**				**> 53 cm**
Density class[a]	**1**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**6**
FBFM (undisturbed)	**TU5**	**TU5**	**TU5**	**SH4**	**SH4**	**SH4**	**SH4**	**TL3**	**TL3**	**SB1**	**SB1**	**TL3**	**TL3**	**SB1**	**SB1**	**TL3**	**TL3**	**TU1**
1-hr fuels ($Mg\ ha^{-1}$)	1.79	1.79	1.79	0.38	0.38	0.38	0.38	0.22	0.22	0.67	0.67	0.22	0.22	0.67	0.67	0.22	0.22	0.09
10-hr fuels ($Mg\ ha^{-1}$)	1.79	1.79	1.79	0.51	0.51	0.51	0.51	0.98	0.98	1.34	1.34	0.98	0.98	1.34	1.34	0.98	0.98	0.40
100-hr fuels ($Mg\ ha^{-1}$)	1.34	1.34	1.34	0.09	0.09	0.09	0.09	1.25	1.25	4.91	4.91	1.25	1.25	4.91	4.91	1.25	1.25	0.67
Fuel bed depth (m)	0.45	0.45	0.45	1.34	1.34	1.34	1.34	0.13	0.13	0.45	0.45	0.13	0.13	0.45	0.45	0.13	0.13	0.27
FBFM (disturbed)[b]	**SH5**	**SH5**	**SH5**	**SH6**	**SH6**	**SH6**	**SH6**	**TU1**	**TU1**	**SB2**	**SB2**	**TU1**	**TU1**	**SB2**	**SB2**	**TU1**	**TU1**	**TU5**
1-hr fuels ($Mg\ ha^{-1}$)	1.61	1.61	1.61	1.29	1.29	1.29	1.29	0.09	0.09	2.01	2.01	0.09	0.09	2.01	2.01	0.09	0.09	1.79
10-hr fuels ($Mg\ ha^{-1}$)	0.94	0.94	0.94	0.65	0.65	0.65	0.65	0.40	0.40	1.90	1.90	0.40	0.40	1.90	1.90	0.40	0.40	1.79
100-hr fuels ($Mg\ ha^{-1}$)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.67	1.79	1.79	0.67	0.67	1.79	1.79	0.67	0.67	1.34
Fuel bed depth (m)	2.68	2.68	2.68	0.89	0.89	0.89	0.89	0.27	0.27	0.45	0.45	0.27	0.27	0.45	0.45	0.27	0.27	0.45

[a]1 - seedling, 2 - sapling, 3 - open, 4 - moderately dense, 5 - dense, 6 - multi-layer

[b]State is disturbed if fire or treatment has occured during previous stage

Adapted from (Scott and Burgan 2005, Rebain 2008)

Table 3.4 – Weather conditions for simulated wildfires

Weather parameter	**Value**
6-m Wind speed (km hr^{-1})	21
Wind direction	Upslope
Air temperature (°C)	31
Herbaceous fuel moisture (%)	40
Woody fuel moisture (%)	70

(Stephens et al. 2009, Rebain 2010)

Table 3.5 – Fire Mortality by Tree Height and Crown Ratio for Applicable Fire Behavior Fuel Models

FIre Behavior Fuel Model	Crown Ratio / Height	0.20	0.30	0.40	0.50	0.60	0.70	0.80
SB1	50	0	0	0	0	24	32	35
FIre	75	0	0	0	0	0	0	29
Mortality	100	0	0	0	0	0	0	17
(%)	125	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0
SB2	50	98	98	98	98	98	98	98
FIre	75	98	98	98	98	98	98	98
Mortality	100	0	32	42	62	78	86	91
(%)	125	0	0	14	33	38	48	61
	150	0	0	0	13	32	35	41
	175	0	0	0	0	21	32	35
	200	0	0	0	0	0	28	33
SH4	50	98	98	98	98	98	98	98
FIre	75	98	98	98	98	98	98	98
Mortality	100	97	98	98	98	98	98	98
(%)	125	0	34	50	71	84	90	93
	150	0	0	29	35	45	60	72
	175	0	0	0	28	34	40	50
	200	0	0	0	0	31	34	39
SH5	50	98	98	98	98	98	98	98
FIre	75	98	98	98	98	98	98	98
Mortality	100	98	98	98	98	98	98	98
(%)	125	98	98	98	98	98	98	98
	150	98	98	98	98	98	98	98
	175	98	98	98	98	98	98	98
	200	98	98	98	98	98	98	98

Table 3.5 (Continued) – Fire Mortality by Tree Height and Crown Ratio for Applicable Fire Behavior Fuel Models

Fire Behavior Fuel Model	Crown Ratio	0.20	0.30	0.40	0.50	0.60	0.70	0.80
	Height							
SH6	50	98	98	98	98	98	98	98
FIre	75	98	98	98	98	98	98	98
Mortality	100	98	98	98	98	98	98	98
(%)	125	98	98	98	98	98	98	98
	150	94	97	98	98	98	98	98
	175	24	41	67	83	90	93	95
	200	0	19	34	47	64	77	85
TL3	50	0	0	0	0	0	0	0
FIre	75	0	0	0	0	0	0	0
Mortality	100	0	0	0	0	0	0	0
(%)	125	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0
TU1	50	0	0	0	0	0	0	0
FIre	75	0	0	0	0	0	0	0
Mortality	100	0	0	0	0	0	0	0
(%)	125	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0
TU5	50	98	98	98	98	98	98	98
FIre	75	98	98	98	98	98	98	98
Mortality	100	98	98	98	98	98	98	98
(%)	125	20	39	64	82	89	93	95
	150	0	0	32	38	52	67	78
	175	0	0	0	31	35	43	55
	200	0	0	0	14	32	35	41

Table 3.6 – Parameter values for treatment-generated woody material utilization and decay rates, and the market value of stored forest carbon

	Parameter	Value or Equation
Biomass utilization (Jenkins et al. 2003)	Total aboveground biomass (TAB): Foliage (F): Stem wood (SW): Stem bark (SB): Branches & tops (BT):	exp[-2.2304 + 2.4435 * ln(dbh)] TAB * exp[-2.9584 + (4.4766 / dbh)] TAB * exp[-0.3737 - (1.8055 / dbh)] TAB * exp[-2.0980 - (1.1432 / dbh)] TAB - (F + SW + SB)
Wood Products (J. Reeb, pers. comm.)	Long-term storage: Lumber: Shavings: Sawdust: Short-term storage: Chips: Sawdust:	 45% 12% 9% 32% 2%
Decay Rates (Spies et al. 1988)	Naturally-killed trees: Treatment-killed trees: Foliage Stem bark Branches & tops Stem wood	$3\%\ yr^{-1}$ 100% immediate emission 100% immediate emission 100% immediate emission Allocated to long- or short-term storage pools
(Winjum et al. 1998)	Long-term storage: Short-term storage:	$1\%\ yr^{-1}$ 100% immediate emission
OTC Carbon Price (Hamilton et al. 2008)		$\$5.83\ Mg^{-1}$

Table 3.7 – Solution time, number of states at final stage, and machine used for simulation for each forest type

Forest Type	Sample No.	Simulation TIme (minutes)	Final Stage State Space	Machine
Mesic-wet Douglas-fir western hemlock	0	35	11787937	T3500
	1	32	8032344	MT960
	2	16	5555542	T3500
	3	33	7887350	MT960
	4	31	8510211	T3500
	5	33	8707780	MT960
	6	30	8769355	T3500
	7	36	8268867	MT960
	8	37	6297229	E5400
	9	44	9905682	E5400
Dry-mesic Douglas-fir-western hemlock	0	661	222957066	T3500
	1	226	47156526	MT960
	2	794	272033437	T3500
	3	61	16223075	MT960
	4	257	56144730	MT960
	5	41	9369567	MT960
	6	37	9730164	MT960
	7	195	56965810	T3500
	8	40	9765050	MT960
	9	158	32689252	MT960
Mediterranean California mixed evergreen	0	86	20609599	MT960
	1	398	139524246	T3500
	2	111	15185911	E5400
	3	538	151942639	MT960
	4	46	10081303	MT960
	5	66	14128113	MT960
	6	998	275944951	MT960
	7	444	102193789	MT960
	8	298	97062714	T3500
	9	689	223946571	T3500

Table 3.8 – Optimal carbon storage compared to control scenarios for each forest type

Forest Type	Sample No.	Initial Stand C	Optimal C (Mg ha-^{1})	Optimal C-100 year Gain (Mg ha^{-1})	Control C (Mg ha^{-1})	Control C 100-year Gain (Mg ha^{-1})	Difference Between Control & Optimal (Mg ha^{-1})	% Difference Between Control & Optimal
Mesic-wet	0	238.83	741.86	503.03	648.10	409.27	(93.76)	23%
Douglas-fir	1	266.94	779.95	513.01	729.79	462.85	(50.17)	11%
western	2	156.77	628.84	472.07	628.84	472.07	0.00	0%
hemlock	3	291.88	756.29	464.41	700.00	408.12	(56.29)	14%
	4	276.83	769.53	492.69	659.02	382.19	(110.51)	29%
	5	345.19	680.26	335.07	659.05	313.85	(21.22)	7%
	6	358.38	764.47	406.09	725.88	367.51	(38.58)	10%
	7	193.04	783.14	590.09	656.01	462.96	(127.13)	27%
	8	309.43	656.90	347.47	656.90	347.47	0.00	0%
	9	172.63	785.88	613.25	716.28	543.64	(69.60)	13%
Dry-mesic	0	88.67	669.69	581.02	596.83	508.16	(72.87)	14%
Douglas-fir-	1	119.61	683.20	563.59	589.24	469.64	(93.96)	20%
western	2	129.19	636.00	506.81	555.50	426.31	(80.50)	19%
hemlock	3	226.61	746.09	519.48	602.56	375.94	(143.53)	38%
	4	85.57	749.92	664.35	635.78	550.21	(114.14)	21%
	5	315.07	813.82	498.74	692.32	377.24	(121.50)	32%
	6	274.26	749.15	474.89	704.96	430.70	(44.19)	10%
	7	179.07	737.52	558.45	633.46	454.39	(104.06)	23%
	8	175.87	795.39	619.52	720.13	544.26	(75.26)	14%
	9	70.85	784.99	714.14	651.59	580.73	(133.40)	23%
Mediterranean	0	102.57	825.82	723.25	668.21	565.64	(157.61)	28%
California	1	90.34	705.51	615.17	598.73	508.39	(106.78)	21%
mixed	2	131.70	758.14	626.44	634.67	502.96	(123.48)	25%
evergreen	3	128.00	716.70	588.70	592.80	464.80	(123.90)	27%
	4	106.14	716.55	610.41	590.48	484.34	(126.07)	26%
	5	190.41	757.97	567.56	587.66	397.25	(170.31)	43%
	6	102.57	636.22	533.65	509.02	406.45	(127.21)	31%
	7	58.13	637.11	578.98	540.29	482.16	(96.82)	20%
	8	124.99	692.37	567.37	592.50	467.51	(99.86)	21%
	9	70.26	670.98	600.71	580.94	510.68	(90.03)	18%

Table 3.9 – Optimal treatment regimes for each forest type (% basal area removed)

Forest Type	Sample No.	Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90
Mesic-wet	0	0	0	15%	0	0	0	15%	0	0	0
Douglas-fir	1	0	0	0	0	15%	0	0	0	0	0
western	2	0	0	0	0	0	0	0	0	0	0
hemlock	3	0	0	0	15%	0	0	0	0	0	0
	4	0	0	15%	0	0	0	0	0	0	0
	5	0	0	0	0	15%	0	0	0	0	0
	6	0	0	0	15%	0	0	0	0	0	0
	7	0	0	15%	0	0	15%	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	15%	0	15%	0	0	0	0
Dry-mesic	0	0	0	0	15%	0	0	15%	0	0	0
Douglas-fir-	1	0	0	0	15%	0	15%	0	0	0	0
western	2	0	0	0	15%	0	15%	0	0	0	0
hemlock	3	0	15%	0	0	15%	0	0	0	0	0
	4	0	0	15%	15%	15%	0	15%	0	0	0
	5	0	15%	15%	0	15%	0	0	0	0	0
	6	0	0	0	0	15%	0	0	0	0	0
	7	0	0	15%	0	15%	0	15%	0	0	0
	8	0	0	0	15%	0	15%	0	0	0	0
	9	0	0	15%	15%	15%	0	15%	0	0	0
Mediterranean	0	0	15%	15%	15%	15%	0	0	0	0	0
California	1	15%	0	0	0	15%	0	15%	0	0	0
mixed	2	0	0	15%	15%	15%	0	15%	0	0	0
evergreen	3	0	0	15%	15%	15%	0	15%	0	0	0
	4	0	0	15%	15%	15%	15%	0	0	0	0
	5	0	15%	15%	15%	15%	15%	0	0	0	0
	6	0	0	15%	15%	15%	0	15%	0	0	0
	7	0	0	0	15%	15%	15%	15%	0	0	0
	8	0	0	15%	15%	0	15%	0	0	0	0
	9	0	0	0	15%	15%	0	15%	0	0	0

CHAPTER 4

THE IMPACT OF STAND LOCATION ON OPTIMAL MANAGEMENT REGIMES FOR INCREASING CARBON STORAGE IN FIRE-PRONE WESTERN OREGON FORESTS

4.1 ABSTRACT

In fire-prone forests, the spatial location of a stand relative to access roads is critical to ground-based response time related to fire suppression efforts. Slope position relative to access roads can affect the size of a contained fire and also the overall carbon emissions among containment scenarios. The spatial location of a stand and its effect on fire suppression efforts can impact the expected severity of wildfire given the occurrence, as well as the optimal management regime (i.e., harvest intensity and timing) for maximizing aboveground carbon storage in fire-prone forests. Stand and weather conditions dictate the rate of fire spread, while stand location directly influences response time by accessibility and the size of the fire at the time of initial suppression efforts. Carbon emissions increase with fire severity and area burned, both of which can be controlled by effective fire suppression.

This paper determines location-dependent management regimes that maximize aboveground carbon storage from Douglas-fir *(Pseudotsuga menziessi)* dominant forests in western Oregon with fire-suppression efforts. The stand location with respect to roads is examined, specifically in terms of the effect that access distance and slope position have on the optimal timing and intensity of fuel treatments and silvicultural activities. Optimal regimes are determined for a range of forest stands, varying by stand distance-to-road and the slope location of the road above or below the stand.

Results suggest that stand slope position relative to access roads did impact fire suppression efforts by affecting the response time and the type of suppression effort (e.g., head attack or rear attack). However, neither stand location nor fire

suppression efforts appeared to impact the maximization of aboveground terrestrial carbon storage in forests and long-lived wood products under the study conditions. It is hypothesized that both stand location and fire suppression efforts would impact the maximization of aboveground terrestrial carbon in forests and wood products under more severe weather conditions, on steeper slopes, and over larger stand areas.

4.2 INTRODUCTION

A century or more of fire suppression efforts in the western U.S. has led to an increased stocking level and fuel load in many forests, which is thought to be responsible for the larger, more intense and severe forest fires. A changing climate, in response to rising levels of atmospheric greenhouse gases (e.g., carbon dioxide), has also contributed to the increased wildfire activity. The increase in fire severity and intensity provides for greater carbon dioxide emissions, therefore becoming part of a positive feedback loop for even greater fire-related emissions if the climate continues towards creating drier weather conditions in fire-prone forests.

Determining optimal management strategies for increasing carbon storage in forests is a complex process. There are many parameters that affect aboveground carbon storage and emission, especially in the disturbance-prone forests of the western United States. Disturbance events, both natural (e.g., wildfire) or anthropogenic (e.g., fuel treatments), have the most potential for impacting forest-based terrestrial carbon storage (Ryan et al. 2010). However, whether the impact on net carbon storage is positive or negative depends heavily on harvest intensity and the timing of treatments (Harmon et al. 2009) or the severity of wildfire (Campbell et al.

2007). While there has been some research on the effects of harvest intensity and timing, the severity of wildfire, and the interaction of these three parameters on aboveground carbon storage (Reinhardt and Holsinger 2010, Vanderberg et al. 2011, Hurteau and North 2009); there are also other variables to consider that can increase the expediency of optimal management regimes (i.e., silvicultural decisions made at discrete time stages).

One important factor in determining how to optimally manage forests for carbon storage in the western U.S. is the spatial location of the stand and the response to features that impact fire behavior and suppression. In fire-prone forests, the location of a stand relative to access roads is critical to ground-based response time and fire suppression efforts and can make the difference between a successfully contained fire and a catastrophic event. Not only can stand location in relation to roads potentially save a catastrophic loss of carbon due to fire-related emissions, it can affect the size of a contained fire, and also the overall carbon emissions among containment scenarios. Therefore, the spatial location of a stand and its effect on fire suppression efforts can impact the expected severity of wildfire given the occurrence. It follows that the spatial location of a stand can affect the optimal management regime (i.e., harvest intensity and timing) for maximizing aboveground carbon storage in fire-prone forests.

This paper attempts to determine location-dependent management regimes that maximize aboveground carbon storage from Douglas-fir *(Pseudotsuga menziessi)* dominant forests in western Oregon with the presence of available fire-suppression. The stand location in respect to roads is examined, specifically in terms of the effect that access distance and slope position have on the optimal timing and intensity of fuel treatments and silvicultural activities. The objective of this research is to develop an understanding of where optimal management regimes for maximizing carbon storage might best be spatially applied given a network of forest roads. Optimal regimes are determined for a range of forest stands, varying by stand distance-to-road and the slope location of the road above or below the stand.

This paper builds on previous work in the field of operations research applied to forest management problems where a series of decisions over time lead to an optimal solution. Optimal management regimes have been determined for a range of western forest conditions, although most prior studies have focused maximizing monetary returns or timber volume (Brodie and Kao 1979, Martin and Ek 1981, Brukus and Brodie 1999). Many of these studies have used some form of dynamic programming, which is logical choice given the non-linear nature of parameters used to model forest systems and formulate objective functions for the determination of optimal solutions (Sessions 1979, Haight et al. 1985, Paredes and Brodie 1987, Graetz and Bettinger 2005, Bettinger et al. 2005, Graetz et al. 2007). The analysis presented here uses probabilistic dynamic programming, in conjunction with forest growth, fire behavior, and fire suppression modeling to create a framework for determining the impact of stand location and fire suppression on maximizing carbon stocks in forests and wood products.

4.3 METHODS

4.3.1 Stand Sample Selection

The impact of fire suppression efforts and stand location on optimal management regimes were computed at the stand level for three Douglas-fir dominated forest types in western Oregon (Hann et al. 2004, Schmidt et al. 2002) (Figure 4.1). Ten plot samples from the three forest types were selected from the Forest Inventory and Analysis (FIA) database (http://fia.fs.fed.us) based on both stand age and density for an initial “conservative” fire suppression scenario (Table 4.1). Six other plots were selected and split into two groups (“immediate action” and “ zero-morality”) for the sensitivity analysis of fire suppression scenarios on the optimization model performance (Table 4.2). All plot samples were restricted to mature stands between the ages of 40 and 140 years to ensure the performance of the growth and mortality model (Curtis 1994). Stands were also restricted to those with tree densities sufficient to make silvicultural treatments feasible, and stands with basal areas below minimum densities were excluded from the analysis.

4.3.2 Silvicultural Treatments

In order to mimic changes in forest structure, silvicultural treatments were simulated as low-thinnings with a range from 15 to 75% reduction in stand basal area at intervals of 15%. The inclusion of thin-from-below treatments across a range of intensities allowed for the representation of changes in forest composition, by simulating the removal of younger trees of species other than those that are more mature. To simulate the effect of no management activity on a stand, a treatment was included to serve as a growth and mortality control. 6 treatments were applied to 10 stand samples for a total of 60 initial condition treatment analysis combinations, 10 of which were grow-only control scenarios.

4.3.3 Forest Growth, Fire Behavior and Suppression

The logic behind the modeling efforts in this paper followed the work of Kline (2004), which suggests four possible outcomes for a stand: 1) growth, 2) growth and fire occurrence, 3) treatment and growth, and 4) treatment, growth and fire occurrence (Figure 4.2). The growth and growth-related mortality, as well as fire behavior and mortality simulations were handled by the network generation algorithm presented by Vanderberg et al. (Chapter 3), since initial stand characteristics fell within the acceptable range. The same weather conditions and slope steepness (35%) were also used. However, fire spread and containment modeling (Fried and Fried 1996) for a 104 hectare stand was included within the fire behavior simulation module to implement the logic suggested by Kline (2004). The modeled stand was a rectangle overlaid on a hillslope with a slope distance of 1610 meters and a width of 645 meters (Figure 4.3). Fire size and shape of a point source fire was assumed to be elliptically shaped and dependant on maximum rate of spread, effective wind speed, and elapsed time for which the fire was spreading at an assumed constant rate (Andrews 2009). The containment modeling made use of multiple fire suppression resources with various production rates and arrival times, as well as the potential for direct attack of the fire ellipse at either the head or the rear depending on the slope location of the stand with respect to access roads (Fried and Fried 1996, Andrews et al. 2008).

4.3.4 Stand Location and Suppression Access

The impact of stand location was simulated by 8 scenarios, varying by ignition point distance-to-road and the location of the ignition point when compared to the road access, above or below the stand (Figures 4.4 - 4.5). If the road location was above the ignition point, then the suppression tactic was classified as a head attack, whereas a road location below the ignition point necessitated a rear attack. Furthermore, rear attacks were simulated at ignition point distances of 0, 403, 805, and 1208 meters from the lower access road, while head attacks were simulated at distances of 403, 805, 1208, and 1610 meters from the upper access road. The fire ignition point distance-to-road also influenced the overall response time of the fire suppression resources.

Three versions of the model (Table 4.3) were run to test the sensitivity of optimal management regimes to response time and fire-related mortality. The “conservative” level of fire suppression effort assumes a one hour reporting time and an average fire-fighting resource with appropriate response times and production rates (Donovan and Rideout 2003, Gonzalez-Caban 1983). The “immediate action” level of fire suppression efforts assumes a six minute reporting time and that fire suppression activities are underway in the immediate area, while utilizing the same fire-fighting resources as the conservative model. The “zero-mortality” version of the model assumes a six minute reporting time and a ten minute response time for aerial suppression efforts for maximum fire-suppression results (Gonzalez-Caban et al. 1984)

Tables 4.4 and 4.5 show the lookup tables for the “conservative” and ”immediate action” fire suppression scenarios, respectively by fire behavior fuel model, fire ignition point distance-to-road, and road location above or below the stand. BehavePlus 5.0 was used to simulate the effects of fire suppression efforts on fire spread and containment, and to estimate the stand area burned and cost of suppression efforts (Andrews 2009, Andrews et al. 2008). “Conservative” scenarios affected 0.47% to 78.55% of the total stand area, and had suppression costs ranging from $1887 to $5957 for stands below the road, while stands above the road had 0.55% to 78.55% of the stand area affected by fire mortality and suppression costs of $1920 to $5140. “Immediate action” scenarios affected 0 to 78.55% of the total stand area, and had suppression costs ranging from $3815 to $4762 for stands below the road, while stands above the road had 0 to 78.55% of the stand area affected by fire mortality and suppression costs of $3800 to $4557. The differences in stand area burned and cost of suppression are a result of the number and duration of resources used for suppression efforts, the resource arrival time due to ignition point distance-to-road and fire-reporting time, and the suppression tactic employed. Some simulated fires escaped before containment, which resulted in the maximum area burned and lower resource costs compared to fires of smaller sizes that could be contained. The “zero-mortality” fire suppression scenario assumed no fire mortality and, subsequently, fire effects and suppression were not simulated.

4.3.5 Optimization Approach and Fire Suppression Costs

Carbon in standing trees, both alive and dead, was calculated in the model by way of allometric biomass equations to obtain the oven-dry mass of individual trees (Jenkins et al. 2003). A factor of 0.50 was applied to the oven-dry mass to determine the aboveground carbon content of forest stands at each state (Matthews 1993). The objective function applied in the dynamic programming optimization algorithm of the model was formulated by the methods of (Vanderberg et al. 2011), and is shown in Eqn. 2 below:

$$f_t(s, x_t) = x_t C[u_r u_d (1 - d_u L) + u_w (1 - d_{cwd} L) + u_r (1 - u_d)] \qquad (2)$$

Where:

	$f_t(s, x_t)$	= carbon storage value due to decision x_t at stage t and state s
	C	= basal area to Mg C conversion
	u_r	= woody material utilization rate
	u_d	= fraction of utilized material subject to decay
	d_u	= decay rate for utilized woody material
	L	= decay horizon ($T - t$)
	u_w	= fraction of non-utilized material ($1 - u_r$)
	d_{cwd}	= decay rate for non-utilized woody material

Rates for the parameters u_r, u_d, d_u, u_w, and d_{cwd} are shown in Table 4.6, as well as the monetary value of carbon stored in forests and wood products. T is equal to the overall planning horizon, which is 100 years, while t is equal to the length of time that has passed since the inception of the model run.

Dynamic programming using backwards recursion was used to determine the optimal management regime for each stand. The optimal management regime was the regime in which the decision at each stage maximized the carbon storage return over the 100-year planning horizon. At each stage *t*, the probability of events $F^*_{t+1}(x_t)$ and $F^*_{t+1}(x_{tfire})$ were used to calculate the expected value of the maximum carbon storage for stage *t*+1 given decision x_t (Eqn 3). Maximum terrestrial carbon returns from storage in the forest stand and wood products are then calculated as the recursion ends at stage 0. Optimal management regime pathways over time were then determined by a search algorithm in the optimization model.

$$F^*_t(s) = \max_{x_t}\{ f_t(s, x_t) + [(1-P)F^*_{t+1}(x_t) + (P)F^*_{t+1}(x_{tfire})]\} \quad \text{for } t = 0,1,\ldots,T \qquad (3)$$

Where:

$F^*_t(s)$	= maximum carbon storage for stage *t* and beyond, given state *s* at stage *t*
x_t	= decision variable that determines the destination state at stage *t* (ba per ha removed at the beginning of stage *t*)
$f_t(s, x_t)$	= carbon storage value due to decision x_t at stage *t* and state *s*
$F^*_{t+1}(x_t)$	= maximum carbon storage value for stage *t*+1, given decision x_t
$F^*_{t+1}(x_{tfire})$	= maximum carbon storage value for stage *t*+1, given decision x_t and the occurrence of fire
P	= probability of fire occurring during stage *t*+1

Fire suppression costs consisted of the initial fixed mobilization cost of the fire-fighting resource as well as the variable hourly cost of suppression efforts. The duration of fire suppression efforts was the elapsed time from initial attack to fire containment, or until the time of escape if the fire could not be contained. If the fire escaped before the resource arrival time, only the fixed mobilization cost was included in the cost calculation. These costs were tracked within the optimization routine, and were output with the optimal solution.

4.4 RESULTS

4.4.1 Fire Suppression and Maximizing Carbon

The impact of fire suppression activities on maximizing terrestrial carbon stored in forest and in wood products was determined to not be a factor based on this analysis. Initial and optimal carbon storage and fire suppression costs for the "conservative" fire suppression scenario are shown in Table 4.7, while the same can be seen for the "immediate action" and "zero-mortality" scenarios are shown in Table 4.8. The average gain in optimal carbon storage compared to grow-only controls was 589, 558, and 576 Mg ha^{-1}, for conservative, immediate action, and zero-mortality suppression scenarios, respectively.

Likewise, the optimal management regime for maximizing terrestrial carbon storage in forests and wood products was not impacted by fire suppression efforts. Table 4.9 shows optimal 100-year management regimes for the "conservative" fire suppression scenario, while Table 4.10 shows optimal regimes for the "immediate action" and "zero-mortality" scenarios. All sample stands benefited from one or more low thinning entries over the planning horizon, with density reductions no greater than 15% of standing basal area.

4.4.2 Fire Suppression Response Time

What can be gleaned from this analysis is the impact of response time on fire suppression effectiveness and cost. Comparing the BehavePlus 5.0 output for the conservative fire suppression scenario in Table 4.4. and the immediate action scenario in Table 4.5, it can be seen that decreases in response time and ignition point distance-to-road greatly decrease the area burned within the stand. The cost of suppression efforts are also similarly impacted, but to a lesser degree. However, the overall results of the analysis suggested that the slope position and the location of the stand in relation to a current road network does not impact the optimality of management regimes under the simulated conditions.

4.5 DISCUSSION

4.5.1 Fire Suppression and Maximizing Carbon

Fire suppression by ground-based methods (e.g., engines, handcrews, and other machinery) is less expensive when compared to aerial methods (González-Cabán 1983, Gonzalez and Caban et al. 1084), which is attractive in an age where overall fire suppression costs are ever increasing (Donovan and Brown 2005). The results of this analysis show no benefit in optimal management regimes for storing aboveground carbon in forests and wood products with the inclusion of fire suppression activities. The range of fire suppression efforts included both ground-based and aerial methods, but neither resulted in increases in maximum carbon storage.

4.5.2 Model Limitations

The results are in agreement with the modeling efforts conducted by Vanderberg et al. (Chapter 3), but suggest that the scope of the analysis was limited by several factors. The weather conditions were assumed constant throughout the analysis, as well as the hillslope of the stand. This limited the fire behavior to that subject to those conditions, where two of the fire behavior fuel models showed no mortality even when given a fire occurrence. A more dynamic relationship between fire behavior and stand conditions should be established in the future, and modeling should be conducted under a range of weather conditions and hillslopes. Furthermore, the spatial extent of the modeled stand is a boundary based only on the average slope distance for the forest regions in this study and the maximum width of the fire spread ellipse modeled by BehavePlus 5.0 under constant weather and stand slope conditions. If the affected stand area and stand conditions at every decision state led to some fire-related mortality based on more precise estimates, the results of this study may change significantly.

4.5.3 Costs of Maximizing Carbon Storage

Although the conditions of this analysis did not show an impact of fire suppression and stand location on optimal management regimes for maximizing carbon in forests and wood products, the modeling efforts did show a relationship between suppression costs and stand location. Further research would benefit from focusing on determining the effects of weather and initial stand conditions on optimal management regimes for maximizing carbon storage. The work presented here is a starting point for the further modeling of fire suppression effectiveness and the direct costs involved.

This carbon flux calculations in this study are bounded by the aboveground standing tree biomass and the volume stored in long-lived wood products. To incorporate a full life-cycle assessment, the boundaries could be extended to include emissions created during treatment, transportation, and primary and secondary processing. It would also be beneficial, from a biogenic perspective, to include a measure of total forest productivity in terms of carbon. Furthermore, instead of focusing on just carbon flux, the real impact of pyrogenic and biogenic emissions coming from the forest as well as those emissions from the extraction and transportation of treatment-generated woody material, and production of wood products, should be measured in terms of the their climate change potential (i.e., warming potential). This could be accomplished by summing the gaseous emissions from these activities and assigning GHG or CO2 equivalency values. This is the true environmental (i.e., atmospheric) cost or benefit of management regimes.

4.6 CONCLUSION

The impact of stand location relative to slope and fire suppression activities on optimal management regimes for maximizing carbon storage in fire-prone western Oregon forest was not a factor in this analysis. However, it was shown that maximizing carbon in forests and wood products can be accomplished through the strategic timing of thin-from-below silvicultural treatments to manipulate stand structure and decrease the risk of fire-related mortality. The optimization model employed in this paper suggests that, under the specified conditions, strategically-timed low-thinnings up to 15% in stand basal area reduction can increase carbon storage in three western Oregon forest types of 40 to 120 years in age with initial densities of 192 to 1781 trees per hectare and basal areas of 22.81 to 73.37 m^2 ha^{-1}, and mean fire return intervals from 8 to 400 years.

Further research efforts need to establish a more dynamic link between fire behavior and stand conditions under a range of weather and initial stand conditions. These results show, despite the impact of fire suppression and stand location, that management regimes that maximize the expected carbon storage for the sample stands within the forest types in this study can benefit from the influence of low-thinning treatments and the removal and utilization of treatment-generated woody material to keep the risk of fire-related mortality and subsequent carbon losses at low levels.

The optimization model presented in this paper is applicable to wide range of initial stand conditions, potential silvicultural treatments, and fire-related weather conditions for fire-prone western Oregon forests. The user may benefit by customizing silvicultural treatments and weather conditions for the stand of choice to determine optimal management regimes for forest stands most relevant to management objectives. The model may also be integrated into a geographic decision support system with little modification.

4.7 REFERENCES

Andrews, P.L. 2009. BehavePlus fire modeling system, version 5.0: Variables. Gen. Tech. Rep. RMRS-GTR-213WWW Revised. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 111 p.

Andrews, P.L., C.D. Bevins, and R.C. Seli. 2008. BehavePlus fire modeling system, version 4.0: User's guide. Gen. Tech. Rep. RMRS-GTR-106WWW Revised. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station. 116 p.

Bettinger, P., D. Graetz, and J. Sessions. 2005. A density-dependent stand-level optimization approach for deriving management prescriptions for interior northwest (USA) landscapes. Forest Ecology and Management 217: 171-186.

Brodie, J.D. and C. Kao. 1979. Optimizing thinning in Douglas-fir with three-descriptor dynamic programming to account for accelerated diameter growth. Forest Science 25: 665-672.

Brukus, V. and J.D. Brodie. 1999. Economic optimization of silvicultural regimes for Scots pine using dynamic programming. Baltic Forestry 5(1): 28-34.

Campbell, J., D. Danato, D. Azuma, and B. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, United States. Journal of Geophysical Research 112, G04014, doi: 10.1029/2007JG000451.

Donovan, G.H. and T.C. Brown. 2005. An alternative incentive structure for wildfire management on National Forest land. Forest Science 51(5): 387-395.

Donovan, G.H. and D.B. Rideout. 2003. An integer programming model to optimize resource allocation for wildfire containment. Forest Science 49(2): 331-335.

Fried, J.S. and B.D. Fried. 1996. 2004. Simulating wildfire containment with realistic tactics. Forest Science 42(3): 267-281.

González-Cabán, A. 1983. Economic cost of initial attack and large-fire suppression. Gen. Tech. Rep. PSW-68. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station. 7p.

Gonzalez-Caban, A., C.W. McKetta, and T.J. Mills. 1984. Costs of fire suppression forces based on cost-aggregation approach. Gen. Tech. Rep. PSW-171. Berkeley, CA: USDA Forest Service Pacific Southwest Forest and Range Experiment Station. 16p.

Graetz, D.H., J. Sessions, and S.L. Garman. 2007. Using stand-level optimization to reduce crown fire hazard. Landscape and Urban Planning 80: 312-319.

Graetz, D. and P. Bettinger. 2005. Determining thinning regimes to reach stand density targets for any-aged stand management in the Blue Mountains of eastern Oregon. In: Bevers, M.; Barrett, T.M., comps. 2005. Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium. Gen. Tech. Rep. PNW-GTR-656. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 10 p.

Haight, R.G., J.D. Brodie, and W.G.Dahms. 1985. A dynamic programming algorithm for optimization of lodgepole pine management. Forest Science 31(2): 321-330.

Hamilton, K., M. Sjardin, T. Marcello, and G. Xu. 2008. Forging a frontier: state of voluntary carbon markets 2008. A report by Ecosystem Marketplace and New Carbon Finance. Forest Trends Association, Washington, D.C.

Harmon, M.E., A. Moreno, and J.B. Domingo. 2009. Effects of partial harvest on the carbon stores in Douglas-fir/western hemlock forests: a simulation study. Ecosystems 12: 777-791.

Hurteau, M. and M. North. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modelled wildfire scenarios. Frontiers in Ecology and the Environment 7: 6p. doi:10.1890/080049

James, C., B. Krumland, and P.J. Eckert. 2007. Carbon sequestration in California forests; two case studies in managed watersheds. Report furnished to Sierra Pacific Industries Forestry Division, PO Box 496014, Redding, CA 96049-6014.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, R.A. Birdsey. 2003. National-scale biomass estimators for United States tree species. Forest Science 49(1): 12-35.

Kline, J.D. 2004. Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the nation’s forests. Res. Note PNW-RN-542. Corvallis, OR: USDA Forest Service, Pacific Northwest Research Station. 46 p.

Martin, G.L. and A.R. Ek. 1981. A dynamic programming analysis of silvicultural alternatives for red pine plantation in Wisconsin. Canadian Journal of Forest Research 11: 370 -379.

Matthews, G. 1993. The carbon content of trees. In: Forestry Commission Technical Paper 4, Edinburgh, UK: Forestry Commission.

Paredes, G. and J.D. Brodie. 1987. Efficient specification and solution of the even-aged rotation and thinning problem. Forest Science 33(1): 14-29.

Reinhardt, E. and L. Holsinger. 2010. Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky Mountains. Forest Ecology and Management 259: 1427-1435.

Ryan, M.G., M.E. Harmon, R.A. Birdsey, C.P. Giardina, L.S. Heath, R.A. Houghton, R.B. Jackson, D.C. McKinley, J.F. Morrison, B.C. Murray, D.E.Pataki, and K.E. Skog. 2010. A synthesis of the science on forests and carbon for U.S. forests. Issues in Ecology Rep. No. 13. 16 p.

Sessions, J. 1979. Effects of harvesting technology upon optimal stocking regimes of forest stands in mountainous terrain. Ph.D. thesis, School of Forestry, Oregon State University, Corvallis, Or. 259 p.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forest of western Oregon and Washington. Ecology 69(6): 1689-1702.

Vanderberg, M.R., K. Boston, and J. Bailey. 2011. Maximizing carbon storage in the Appalachians: a method for considering the risk of disturbance events. IN: Proceedings of the 17th Central Hardwood Forest Conference. Lexington, KY. April 5-7. U.S. Department of Agriculture, Forest Service, Gen. Tech. Rep.

Winjum, J.K., S. Brown, and B. Schlamadinger. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. Forest Science 44(2): 272-284.

Ximenes, F.A., W.D. Gardner, and A.L. Cowie. 2008. The decomposition of wood products in landfills in Sydney, Australia. Waste Management *In Press* doi:10.1016/j.wasman.2007.11.006

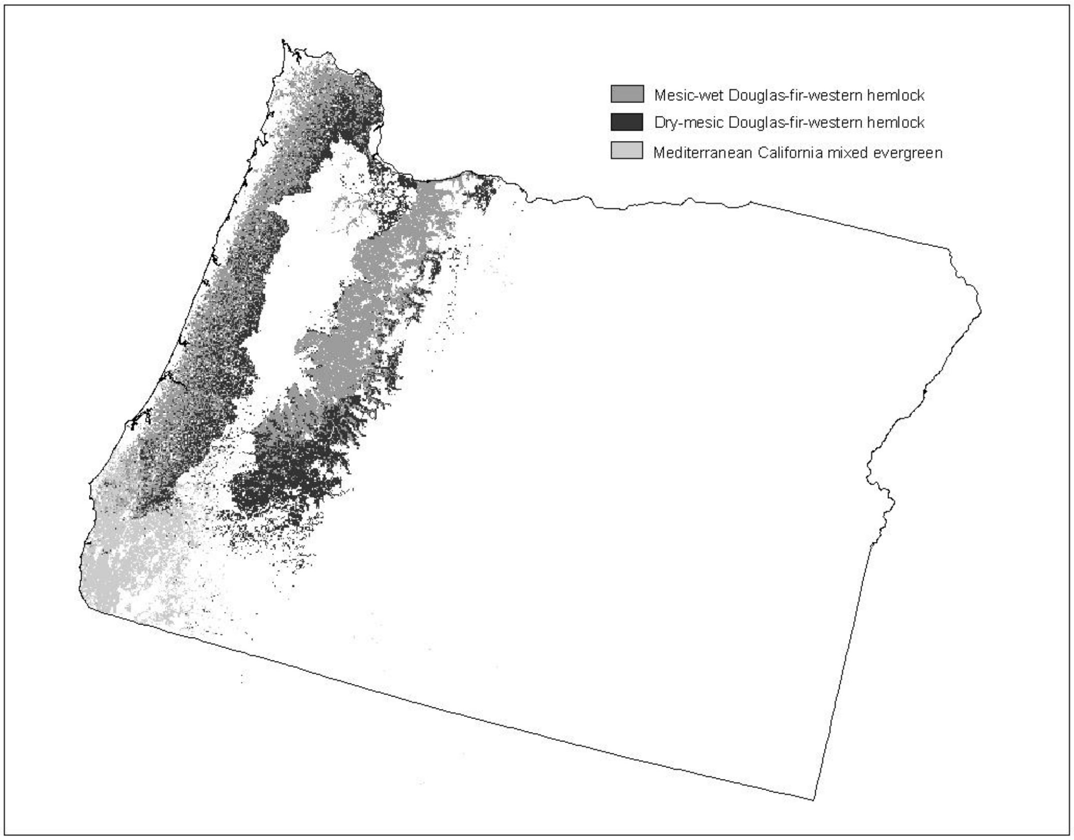

Figure 4.1 – Geographic areas of sampled Douglas-fir-dominated forest types in western Oregon

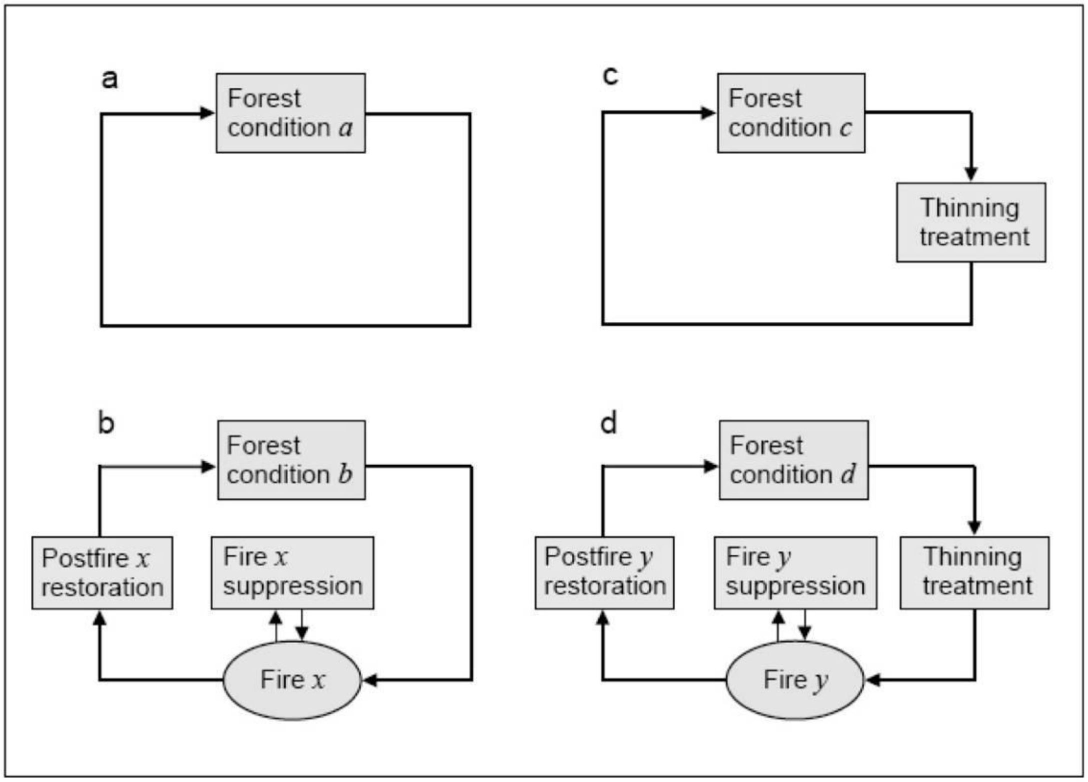

Figure 4.2 – Potential forest condition outcomes (adapted from Kline 2004)

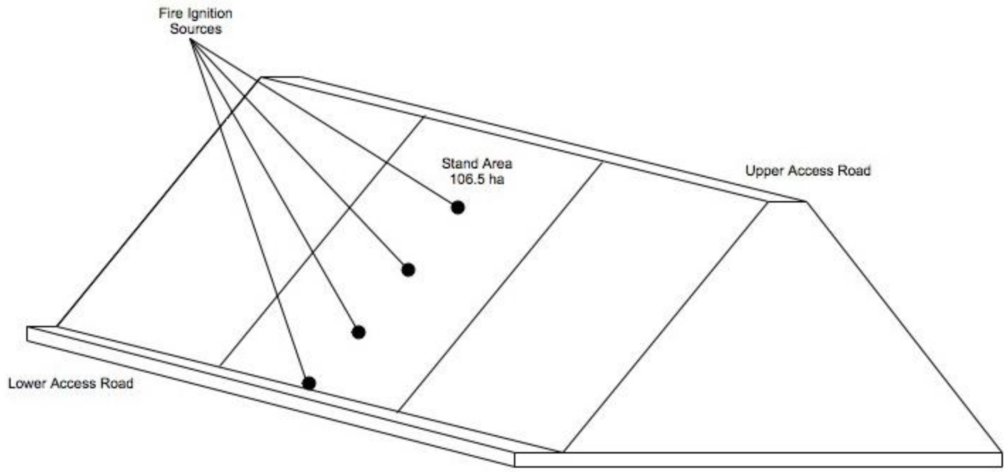

Figure 4.3 – Hillslope showing upper and lower access road locations and fire ignition points

Table 4.1 – Sample stand characteristics by forest type for "Conservative" analyses

Forest type	Sample no.	Age (yrs)	QMD (cm)	Trees ha^{-1}	Basal area (m^2 ha^{-1})	Site index
Mesic-wet Douglas-fir-western hemlock (MWDF)						
	1	100	70.93	192	60.52	127
	2	70	50.05	245	43.36	130
Dry-mesic Douglas-fir-western hemlock (DMDF)						
	3	40	29.47	641	28.39	106
	4	100	51.99	585	73.37	146
	5	80	36.99	658	38.95	68
Mediterranean California mixed evergreen (MCME)						
	6	90	34.65	785	41.26	100
	7	120	36.79	758	35.27	83
	8	110	44.81	892	29.8	90
	9	80	25.49	1781	35.07	71
	10	70	34.57	642	22.81	80

Table 4.2 – Sample stand characteristics by forest type for "Immediate Action" and "Zero Mortality" analyses

Forest type	Sample no.	Age (yrs)	QMD (cm)	Trees ha^{-1}	Basal area (m^2 ha^{-1})	Site index
IMMEDIATE FIRE SUPPRESSION ACTION UPON IGNITION (Response time = 6 min)						
MWDF	1	90	58.23	374	58.08	107
DMDF	2	90	37.59	410	26.69	79
MCME	3	80	25.49	1781	35.07	71
ZERO FIRE MORTALITY						
MWDF	1	100	70.93	192	60.52	127
DMDF	2	70	37.79	596	35.45	84
MCME	3	110	44.81	892	29.8	90

Table 4.3 – Fire suppression scenarios, resources, costs, and production

Resource Description	Elapsed Time to Report (hrs)	Arrival Time to Road (hrs)	Variable Cost ($ hr^{-1})	Fixed Cost	Line Production Rate (km hr^{-1})	Resource Duration (hrs)
			CONSERVATIVE FIRE SUPPRESSION			
Type I Crew	1	0.5	$125	$500	0.20	10
Type II Crew	1	1.0	$175	$600	0.25	12
Engine A	1	1.0	$125	$600	0.15	10
Engine B	1	1.5	$100	$900	0.10	12
Engine C	1	1.5	$75	$400	0.09	14
Dozer	1	2.0	$175	$300	0.36	20
Tractor Plow	1	2.5	$150	$500	0.45	20
			IMMEDIATE ACTION FIRE SUPPRESSION			
Type I Crew	0.1	0.0	$125	$500	0.20	10
Type II Crew	0.1	0.0	$175	$600	0.25	12
Engine A	0.1	0.0	$125	$600	0.15	10
Engine B	0.1	0.0	$100	$900	0.10	12
Engine C	0.1	0.0	$75	$400	0.09	14
Dozer	0.1	0.0	$175	$300	0.36	20
Tractor Plow	0.1	0.0	$150	$500	0.45	20
			ZERO-MORTALITY FIRE SUPPRESSION			
Air Tanker - Fixed Wing						
Small (4230 liters)	0.1	0.17	$813	$60	-	-
Medium (7256 liters)	0.1	0.17	$1,110	$57	-	-
Large (8918 liters)	0.1	0.17	$1,302	$134	-	-
Air Tanker - Rotary Wing						
Small (416 liters)	0.1	0.17	$328	$66	-	-
Medium (1703 liters)	0.1	0.17	$811	$224	-	-
Large (3407 liters)	0.1	0.17	$1,811	$24	-	-

Table 4.4 – Fire area and suppression costs by stand ignition location and applicable fire behavior fuel models (fire-fighting resource production rates = *conservative*)

STAND LOCATION BELOW ROAD					STAND LOCATION ABOVE ROAD				
Fire Behavior Fuel Model	Ignition Point Distance-to-Road (km)	Fire Area (ha)	Stand Area Affected (Total area = 106.5 ha)	Supression Cost	Fire Behavior Fuel Model	Ignition Point Distance-to-Road (km)	Fire Area (ha)	Stand Area Affected (Total area = 106.5 ha)	Supression Cost
SB1	1	21.59	20.27%	$5,057	**SB1**	0.75	5.24	4.92%	$3,800
	0.75	18.22	17.11%	$4,973		0.5	20.92	19.65%	$4,565
	0.5	15.18	14.26%	$4,889		0.25	22.00	20.66%	$5,140
	0.25	5.24	4.92%	$3,815		0	18.09	16.99%	$5,036
SB2	1	83.65	78.55%	$3,890	**SB2**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$2,806		0.5	20.92	19.65%	$3,800
	0.5	20.92	19.65%	$3,800		0.25	47.05	44.18%	$3,883
	0.25	5.24		$3,800		0	83.65	78.55%	$4,424
SH4	1	83.65	78.55%	$4,262	**SH4**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$4,262		0.5	20.92	19.65%	$3,800
	0.5	20.92	19.65%	$4,262		0.25	47.05	44.18%	$3,800
	0.25	5.24	4.92%	$4,262		0	83.65	78.55%	$3,800
SH5	1	83.65	78.55%	$4,762	**SH5**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$4,262		0.5	20.92	19.65%	$3,800
	0.5	20.92	19.65%	$4,262		0.25	47.05	44.18%	$3,800
	0.25	5.24	4.92%	$4,262		0	83.65	78.55%	$3,800
SH6	1	83.65	78.55%	$3,800	**SH6**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$3,800		0.5	20.92	19.65%	$3,800
	0.5	20.92	19.65%	$3,800		0.25	47.05	44.18%	$3,800
	0.25	5.24	4.92%	$3,800		0	83.65	78.55%	$3,800
TL3	1	1.00	0.94%	$1,968	**TL3**	0.75	1.16	1.09%	$3,316
	0.75	0.83	0.78%	$1,941		0.5	0.96	0.90%	$3,283
	0.5	0.67	0.63%	$1,914		0.25	0.75	0.70%	$1,951
	0.25	0.50	0.47%	$1,887		0	0.58	0.55%	$1,920
TU1	1	4.45	4.18%	$3,958	**TU1**	0.75	4.99	4.69%	$3,978
	0.75	3.74	3.52%	$3,913		0.5	4.16	3.91%	$3,923
	0.5	3.12	2.93%	$3,566		0.25	3.37	3.16%	$3,565
	0.25	2.54	2.38%	$3,515		0	2.62	2.46%	$3,498
TU5	1	62.35	58.55%	$5,957	**TU5**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$4,804		0.5	20.92	19.65%	$3,883
	0.5	20.92	19.65%	$3,883		0.25	47.05	44.18%	$4,803
	0.25	5.24	4.92%	$3,873		0	53.66	50.39%	$5,861

Table 4.5 – Fire area and suppression costs by stand ignition location and applicable fire behavior fuel models (fire-fighting resource production rates = *immediate action*)

STAND LOCATION BELOW ROAD					STAND LOCATION ABOVE ROAD				
Fire Behavior Fuel Model	Ignition Point Distance-to-Road (km)	Fire Area (ha)	Stand Area Affected (Total area = 106.5 ha)	Supression Cost	Fire Behavior Fuel Model	Ignition Point Distance-to-Road (km))	Fire Area (ha)	Stand Area Affected (Total area = 106.5 ha)	Supression Cost
SB1	1	0.37	0.35%	$3,936	**SB1**	0.75	0.33	0.31%	$3,945
	0.75	0.25	0.23%	$3,911		0.5	0.21	0.20%	$3,912
	0.5	0.12	0.12%	$3,885		0.25	0.08	0.08%	$3,876
	0.25	0.08	0.08%	$3,858		0	0.04	0.04%	$3,841
SB2	1	2.70	2.54%	$4,161	**SB2**	0.75	5.24	4.92%	$4,557
	0.75	1.79	1.68%	$4,094		0.5	4.16	3.91%	$4,384
	0.5	1.08	1.02%	$4,027		0.25	1.91	1.80%	$4,195
	0.25	0.50	0.47%	$3,954		0	0.58	0.55%	$4,016
SH4	1	83.65	78.55%	$4,262	**SH4**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$4,262		0.5	20.92	19.65%	$3,800
	0.5	20.92	19.65%	$4,262		0.25	47.05	44.18%	$3,800
	0.25	5.24	4.92%	$4,262		0	83.65	78.55%	$3,800
SH5	1	83.65	78.55%	$4,762	**SH5**	0.75	5.24	4.92%	$3,800
	0.75	47.05	44.18%	$4,262		0.5	20.92	19.65%	$3,800
	0.5	20.92	19.65%	$4,262		0.25	47.05	44.18%	$3,800
	0.25	5.24	4.92%	$4,262		0	83.65	78.55%	$3,800
SH6	1	9.32	8.75%	$4,500	**SH6**	0.75	5.24	4.92%	$3,800
	0.75	6.20	5.82%	$4,370		0.5	20.92	19.65%	$3,800
	0.5	3.66	3.44%	$4,239		0.25	47.05	44.18%	$3,800
	0.25	1.71	1.60%	$4,098		0	83.65	78.55%	$3,800
TL3	1	0.04	0.04%	$3,863	**TL3**	0.75	0.00	0.00%	$3,831
	0.75	0.00	0.00%	$3,829		0.5	0.00	0.00%	$3,824
	0.5	0.00	0.00%	$3,822		0.25	0.00	0.00%	$3,816
	0.25	0.00	0.00%	$3,815		0	0.00	0.00%	$3,809
TU1	1	0.08	0.08%	$3,865	**TU1**	0.75	0.04	0.04%	$3,860
	0.75	0.04	0.04%	$3,853		0.5	0.04	0.04%	$3,846
	0.5	0.04	0.04%	$3,841		0.25	0.00	0.00%	$3,831
	0.25	0.00	0.00%	$3,828		0	0.00	0.00%	$3,817
TU5	1	0.83	0.78%	$4,003	**TU5**	0.75	1.00	0.94%	$4,055
	0.75	0.54	0.51%	$3,965		0.5	0.58	0.55%	$3,997
	0.5	0.33	0.31%	$3,927		0.25	0.25	0.23%	$3,933
	0.25	0.17	0.16%	$3,886		0	0.08	0.08%	$3,873

Table 4.6 – Parameter values for treatment-generated woody material utilization and decay rates, and the market value of stored forest carbon

Woody material utilization rate (James et al. 2007)	**0.80**
Utilized woody material annual decay rate (Winjum et al. 1998)	**0.01**
Non-utilized woody material annual decay rate (Spies et al. 1988)	**0.03**
Fraction of utilized material subject to decay (James et al. 2007)	**0.75**
Fraction of utilized material permanently stored (Ximenes et al. 2008)	**0.25**
Carbon Value (Hamilton et al. 2008)	**$5.83/Mg**

Table 4.7 – Initial and optimal carbon storage and fire suppression costs for "Conservative" fire-fighting resource production rates {each sample no. corresponds to all 8 stand locations above and below road}

Sample No.	Initial Stand C	Optimal C (Mg ha^{-1})	Optimal C 100 year Gain (Mg ha^{-1})	Cost of Supression
1	266.94	784.25	517.31	$0.00
2	172.63	802.70	630.07	$0.00
3	85.57	780.62	695.05	$0.00
4	315.07	808.75	493.68	$0.00
5	129.19	652.10	522.91	$0.00
6	131.70	774.64	642.94	$0.00
7	124.99	707.95	582.96	$0.00
8	90.34	720.52	630.18	$0.00
9	102.57	658.48	555.91	$0.00
10	70.26	690.37	620.11	$0.00

Table 4.8 – Initial and optimal carbon storage and fire suppression costs for "Immediate Action" and "Zero-mortality" fire-fighting resource production rates {each sample no. corresponds to all 8 stand locations above and below road}

Sample No.	Initial Stand C	Optimal C (Mg ha-1)	Optimal C 100 year Gain (Mg ha-1)	Cost of Supression
	IMMEDIATE FIRE SUPPRESSION ACTION UPON IGNITION (Response time = 6 min)			
1	238.83	755.89	517.06	$0.00
2	88.67	688.36	599.69	$0.00
3	102.57	658.48	555.91	$0.00
	ZERO FIRE MORTALITY			
4	266.94	784.25	517.31	$0.00
5	119.61	700.96	581.35	$0.00
6	90.34	720.52	630.18	$0.00

Table 4.9 – Optimal treatment regimes for "Conservative" fire-fighting resource production rates (% basal area removed) {each sample no. corresponds to all 8 stand locations above and below road}

Sample No.	Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90
1	0	0	0	0	15%	0	0	0	0	0
2	0	0	0	15%	0	0	15%	0	0	0
3	0	0	15%	15%	0	15%	15%	0	0	15%
4	0	15%	15%	0	0	15%	0	0	0	0
5	0	0	0	15%	0	15%	0	15%	0	0
6	0	0	15%	15%	15%	0	15%	0	0	0
7	0	0	15%	0	15%	0	15%	0	0	0
8	15%	0	0	0	15%	0	15%	0	0	0
9	0	0	15%	15%	15%	0	15%	0	15%	0
10	0	0	0	15%	0	15%	0	15%	0	0

Table 4.10 – Optimal treatment regimes for "Immediate Action" and "Zero-mortality" fire-fighting resource production rates (% basal area removed) {each sample no. corresponds to all 8 stand locations above and below road}

Sample No.	Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60	Year 70	Year 80	Year 90
	IMMEDIATE FIRE SUPPRESSION ACTION UPON IGNITION (Response time = 6 min)									
1	0	0	0	15%	0	0	15%	0	0	0
2	0	0	0	0	15%	0	15%	0	0	0
3	0	0	15%	15%	15%	0	15%	0	15%	0
	ZERO FIRE MORTALITY									
4	0	0	0	0	15%	0	0	0	0	0
5	0	0	0	15%	0	15%	0	15%	0	0
6	15%	0	0	0	15%	0	15%	0	0	0

CHAPTER 5

GENERAL

CONCLUSIONS

5.1 CONCLUSIONS

The objective for many forest restoration activities in fire-prone western forests should include the preparation of stands for the return of a low- or mixed-fire severity regime. Implementing mechanical treatments to create stands more resilient to active or passive crown fire is a major step in restoring functional active-fire conditions (Graham et al. 2004), and as indicated in the results of this study, may store greater amounts of carbon in trees and wood products over time than no treatment at all. If reducing atmospheric carbon levels is an objective, then a silvicultural regime that minimizes fire-related emissions by reducing the probability of wildfire or wildfire-related mortality can be beneficial in fire-prone western forests.

The determination of optimal silvicultural regimes for maximizing carbon storage is incomplete without addressing the uncertainty that surrounds the random nature of fire as disturbance within western forests. Our probabilistic dynamic programming approach utilizes the fire occurrence probability function to optimize silvicultural treatments under such uncertainty. Overall, this modeling and simulation effort suggests that gains in terrestrial carbon storage can be accomplished at the stand level by optimal management regimes. However, this analysis is restricted to those stands within the range of initial conditions presented. The optimal management regime is influenced by treatment intensity, predicted fire mortality, treatment-generated woody material utilization, and potentially the slope position of the stand in respect to access roads.

The results of this study suggest that management regimes that maximize the expected carbon storage for the sample stands within the forest types in this study can benefit from the influence of thin-from-below treatments and the removal and utilization of treatment-generated woody material to keep the risk of fire-related mortality and subsequent carbon losses at low levels.

The results of this study also suggest that creation of forest stands more resilient to disturbance events could be beneficial to carbon storage, and create carbon stores with market values. In regards to the current Voluntary Carbon Standard method of risk management, making decisions with the model can lead to additional carbon storage values that rival the required buffer pool deposits by the hedge method of risk management.

The impact of stand location and fire suppression activities on optimal management regimes for maximizing carbon storage in fire-prone western Oregon forest was not a factor in this analysis. However, it was shown that maximizing carbon in forests and wood products can be accomplished through the strategic timing of thin-from-below silvicultural treatments to manipulate stand structure and decrease the risk of fire-related mortality.

The optimization model is applicable to wide range of initial stand conditions, potential silvicultural treatments, and fire-related weather conditions for fire-prone western Oregon forests. The model may be used to determine optimal management regimes for forest stands, but decisions are restricted to the management unit and does not consider the impact of surrounding stands. The scaling-up of the optimization model may be of use in determining optimal management regimes for planning purposes at the landscape level. The model may also be integrated into a geographic decision support system with little modification.

BIBLIOGRAPHY

Adams, D.M. and G.S. Latta. 2004. Effects of a forest health thinning program on land and timber values in eastern Oregon. Journal of Forestry 102(8): 9-13.

Agee, J.K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Agee, J.K. and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Ager, A.A., R.J. Barbour, and J.L. Hayes. 2005. Simulating fuel reduction scenarios on a wildand-urban interface in northeastern Oregon. In: Bevers, M. and T.M. Barrett, comps. Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium. USDA Forest Service Gen. Tech. Rep. PNW-GTR-656. Portland, OR. pp. 215-227.

Andrews, P.L. 2009. BehavePlus fire modeling system, version 5.0: Variables. Gen. Tech. Rep. RMRS-GTR-213WWW Revised. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 111 p.

Andrews, P.L., C.D. Bevins, and R.C. Seli. 2008. BehavePlus fire modeling system, version 4.0: User’s guide. Gen. Tech. Rep. RMRS-GTR-106WWW Revised. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station. 116 p.

Apps, M.J. and D.T. Price. 1996. Introduction. In: Forest Ecosystems, Forest Management, and the Global Carbon Cycle, (M.J. Apps and D.T. Price, eds). NATO ASI Series 1: Global Environmental Changes, Vol. 40, Springer-Verlag, p. 1-15.

Arno, S.F. and C.E. Fiedler. 2005. Mimicking Nature’s Fire: Restoring Fire-Prone Forests in the West. Island Press, Washington, DC.

Arno, S.F. and S. Allison-Bunnell. 2002. Flames in Our Forest: Disaster or Renewal? Island Press, Washington, D.C.

Arroja, L., A.C. Dias, and I. Capela. 2006. The role of Eucalyptus globules forest and products in carbon sequestration. Climatic Change 74: 123-140.

Backéus, S., P. Wikström, and T. Lämås. 2005. A model for regional analysis of carbon sequestration and timber production. Forest Ecology and Management 216: 28-40.

Bellman, R. E. 1957. Dynamic Programming. Princeton University Press, Princeton, New Jersey. 340 p.

Bergman, R. and J. Zerbe. 2004. Primer on wood biomass for energy. USDA Forest Service, State and Private Forest Technology Marketing Unit, Forest Products Laboratory, Madison, WI. 10 p.

Berry, A.H. and H. Hesseln. 2004. The effect of the wildland-urban interface on prescribed burning costs in the Pacific Northwestern United States. Journal of Forestry 102(6): 33-37.

Bettinger, P., D. Graetz, and J. Sessions. 2005. A density-dependent stand-level optimization approach for deriving management prescriptions for interior northwest (USA) landscapes. Forest Ecology and Management 217: 171-186.

Birdsey, R., Pregitzer, K., Lucier, A. 2006. Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality 35: 4197-4202.

Birdsey, R., R. Alig, and D. Adams. 2000. Mitigation activities in the forest sector to reduce emissions and enhance sinks of greenhouse gases. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-59 pp. 112-131.

Brodie, J.D. and C. Kao. 1979. Optimizing thinning in Douglas-fir with three-descriptor dynamic programming to account for accelerated diameter growth. Forest Science 25: 665-672.

Brockway, D.G., R.G. Gatewood, and R.B. Paris. 2002. Restoring grassland savannas from degraded pinyon-juniper woodlands: Effects of mechanical overstory reduction and slash treatment alternatives. Journal of Environmental Management 64: 179-197.

Brown, S. 2002. Measuring, monitoring, and verification of carbon benefits for forest-based projects. Philosophical Transactions of the Royal Society of London 360: 1669-1683.

Brown, P.M., M.R. Kaufmann, and W.D. Shepperd. 1999. Long-term landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology 14: 513-532.

Brukus, V. and J.D. Brodie. 1999. Economic optimization of silvicultural regimes for Scots pine using dynamic programming. Baltic Forestry 5(1): 28-34.

Brunson, M.W. and B.A. Shindler. 2004. Geographic variation in social acceptability of wildland fuels management in the western United States. Society and Natural Resources 17: 661-678.

Busenberg, G. 2004. Wildfire management in the United States: the evolution of policy failure. Review of Policy Research 21(2): 145-156.

Campbell, J., D. Danato, D. Azuma, and B. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, United States. Journal of Geophysical Research 112, G04014, doi: 10.1029/2007JG000451.

Carle, D. 2002. Burning Questions: America's Fight with Nature's Fire. Praeger Publishers, Westport, CT.

Casperson, J.P., S.W. Pacala, J.C. Jenkins, G.C. Hurtt, P.R. Moorcraft, and R.A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. forests. Science 290(10): 1148-1151.

Cathcart, J., A.A. Ager, A. McMahon, M. Finney, and B. Watt. 2010. Carbon benefits from fuel treatments. In: Jain, T.B.; Graham, R.T.; and Sandquist, J., tech. eds. 2010. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate: Proceedings of the 2009 National Silviculture Workshop, Boise, ID. RMRS-P-61. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 351 p.

Chameides, W. and M. Oppenheimer. 2007. Carbon trading over taxes. Science 315(5819): 1670.

Chase, A. 2001. In a Dark Wood: The Fight Over Forests and the Myths of Nature. Transaction Publishers 535 pp. ISBN 0765807521

Chen, J., S.J. Columbo, M.T. Ter-Mikaelian, and L.S. Heath. 2010. Carbon budget of Ontario's managed forests and harvested wood products, 2001-2100. Forest Ecology and Management 259: 1385-1398.

Cuiping, L., Yanyongjie, W. Chuangzhi, and H. Haitao. 2004. Study on the distribution and quantity of biomass residues resource in China. Biomass & Bioenergy 27(2): 111-117.

Curtis, R.O., G.W. Clendenen, and D.J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. Gen. Tech. Rep. PNW-128. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Research Station. 79 p.

Curtis, R.O. 1994. Some simulation estimates of mean annual increment of Douglas-fir: Results, limitations, and implications for management. Research Paper PNW-RP-471. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 33 p.

Davis, S.C., A.E. Hessl, C.J. Scott, M.B. Adams, and R.B. Thomas. 2009. Forest carbon sequestration changes in response to timber harvest. Forest Ecology and Management 258: 2101-2109.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 1998. Fire's Effects on Ecosystems. John Wiley & Sons, Inc., New York.

Dewar, R.C. 1991. Analytical model of carbon storage in the trees, soils, and wood products of managed forests. Tree Physiology 8: 239-258.

Dias, A.C., M. Louro, L. Arroja, and I. Capela. 2005. The contribution of wood products to carbon sequestration in Portugal. Annals of Forest Science 62: 903-909.

Dombeck, M.P., J.E. Williams, and C.A. Wood. 2004. Wildfire policy and public lands: Integrating scientific understanding with social concerns across landscapes. Conservation Biology 18(4): 883-889.

Donovan, G.H. and T.C. Brown. 2005. An alternative incentive structure for wildfire management on National Forest land. Forest Science 51(5): 387-395.

Donovan, G.H. and D.B. Rideout. 2003. An integer programming model to optimize resource allocation for wildfire containment. Forest Science 49(2): 331-335.

Fiedler, C.E., C.E. Keegan III, D.P. Wichman, and S.F. Arno. 1999. Product and economic implications of ecological restoration. Forest Products Journal 49(2): 19-23.

Fight, R.D., G.L. Pinjuv, and P.J. Daugherty. 2004. Small-diameter wood processing in the southwestern United States: An economic case study and decision analysis tool. Forest Products Journal 54(5): 85-89.

Finney, M.A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management 211: 97-108.

Floyd, L.M., W.H. Romme, and D.H. Hanna. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. Ecological Applications 10(6): 1666-1680.

Fried, J.S. and B.D. Fried. 1996. 2004. Simulating wildfire containment with realistic tactics. Forest Science 42(3): 267-281.

Fule, P.Z., and W.W. Covington. 1998. Spatial patterns of Mexican pine-oak forests under different recent fire regimes. Plant Ecology 134: 197-209.

Fule, P.Z., A.E.M. Waltz, W.W. Covington, and T.A. Heinlein. 2001. Measuring forest restoration effectiveness in reducing hazardous fuels. Journal of Forestry 99(11): 24-29.

Gill, S.J., G.S. Biging, and E.C. Murphy. 2000. Modeling conifer tree crown radius and estimating canopy cover. Forest Ecology and Management 126: 405-416.

González-Cabán, A. 1983. Economic cost of initial attack and large-fire suppression. Gen. Tech. Rep. PSW-68. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station. 7p.

Gonzalez-Caban, A., C.W. McKetta, and T.J. Mills. 1984. Costs of fire suppression forces based on cost-aggregation approach. Gen. Tech. Rep. PSW-171. Berkeley, CA: USDA Forest Service Pacific Southwest Forest and Range Experiment Station. 16p.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C.

Jenkins, G.J. Kohlmaier, W. Kurz, S. Liu, G. Nabuurs, S. Nilsson, and A.Z. Shividenko. 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications 12(3): 891-899.

Graetz, D. and P. Bettinger. 2005. Determining thinning regimes to reach stand density targets for any-aged stand management in the Blue Mountains of eastern Oregon. In: Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium, (Bevers, M. and T.M. Barrett, eds). USDA Forest Service Gen. Tech. Rep. PNW-GTR-656. Portland, OR. pp. 255-264.

Graetz, D.H., J. Sessions, and S.L. Garman. 2007. Using stand-level optimization to reduce crown fire hazard. Landscape and Urban Planning 80: 312-319.

Graham, R.T., S. McCaffrey, and T.B. Jain. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service Gen.Tech. Rep. GTR-RMRS-120. Fort Collins, CO. 43 p.

Graham, R.T., A.E. Harvey, T.B. Jain, and J.R. Tonn. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Service PNW-GTR-463. Portland, OR. 27 p.

Gray, A.N., H.S.J. Zald, R.A. Kern, and M. North. 2005. Stand conditions associated with tree regeneration in Sierran mixed-conifer forests. Forest Science 51(3): 198-210.

Haight, R.G., J.D. Brodie, and W.G.Dahms. 1985. A dynamic programming algorithm for optimization of lodgepole pine management. Forest Science 31(2): 321-330.

Hamilton, K., M. Sjardin, T. Marcello, and G. Xu. 2008. Forging a frontier: state of voluntary carbon markets 2008. A report by Ecosystem Marketplace and New Carbon Finance. Forest Trends Association, Washington, D.C.

Han, H., H.W. Lee, and L.R. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. Forest Products Journal 54(2): 21-27.

Hann, D. 1980. Development and evaluation of an even- and uneven-aged ponderosa pine/Arizona fescue stand simulator. USDA Forest Service Res. Pap. RP-INT-267. 95 p.

Hann, W., A. Shilsky, D. Havlina, K. Schon, S. Barrett, T. DeMeo, K. Pohl, J. Menakis, D. Hamilton, J. Jones, M. Levesque, and C. Frame. 2004. Interagency fire regime condition class guidebook. Last update January 2008: Version 1.3.0 [Homepage of the Interagency and The Nature Conservancy fire regime condition class wevsite, USDA Forest Service, US Department of the Interior, The Nature Conservancy, and Systems for Environmental Management]. [Online]. Available: www.frcc.gov.

Hann, D.W. and C.H. Wang. 1990. Mortality equations for individual trees in southwest Oregon. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. Research Bulletin 67. 17p.

Hann, D.W. and D.R. Larsen. 1991. Diameter growth equations for fourteen tree species in southwest Oregon. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. Research Bulletin 69. 18p.

Harmon, M.E. 2001. Carbon sequestration in forests: addressing the scale question. Journal of Forestry 99(4): 24-29.

Harmon, M.E., A. Moreno, and J.B. Domingo. 2009. Effects of partial harvest on the carbon stores in Douglas-fir/western hemlock forests: a simulation study. Ecosystems 12: 777-791.

Harmon, M.E., S.L. Garman, and W.K. Ferrell. 1996. Modeling historical patterns of tree utilization in the Pacific Northwest: carbon sequestration implications. Ecological Applications 6(2): 641-652.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247: 699-702.

Hartsough, B.R., X. Zhang, and R.D. Fight. 2001. Harvesting cost model for small trees in natural stands in the interior Northwest. Forest Products Journal 51(4): 54-61.

Hashimoto, S., M. Nose, T. Obara, and Y. Moriguchi. 2002. Wood products: potential carbon sequestration and impact on net carbon emissions of industrialized countries. Environmental Science and Policy 5: 183-193.

Heath, L.S., R.A. Birdsey, C. Row, and A.J. Plantinga. 1996. Carbon pools and flux in U.S. forest products. In: Forest Ecosystems, Forest Management, and the Global Carbon Cycle, (M.J. Apps and D.T. Price, eds). NATO ASI Series 1: Global Environmental Changes, Vol. 40, Springer-Verlag, p. 271-278.

Hollenstein, K., R.L. Graham, and W.D. Shepperd. 2001. Biomass flow in western forests: simulating the effects of fuel reduction and presettlement restoration treatments. Journal of Forestry 99(10): 12-19

Hurteau, M.D. and M. North. 2010. Carbon recovery rates following different wildfire risk mitigation treatments. Forest Ecology and Management 260: 930-937.

Hurteau, M.D., B.A. Hungate, and G.W. Koch. 2009. Accounting for risk in valuing forest carbon offsets. Carbon Balance and Management 4(1): 14p. doi:10.1186/1750-0680-4-1

Hurteau, M. and M. North. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modelled wildfire scenarios. Frontiers in Ecology and the Environment 7: 6p. doi:10.1890/080049

Hurteau, M.D., G.W. Koch, and B.A. Hungate. 2008. Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Frontiers in Ecology and the Environment *In Press* doi:10.1890/070187

James, C., B. Krumland, and P.J. Eckert. 2007. Carbon sequestration in California forests; two case studies in managed watersheds. Report furnished to Sierra Pacific Industries Forestry Division, PO Box 496014, Redding, CA 96049-6014.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, R.A. Birdsey. 2003. National-scale biomass estimators for United States tree species. Forest Science 49(1): 12-35.

Karjalainen, T., A. Pussinen, S. Kellomäki, and R. Mäkipää. 1999. Scenarios for the carbon balance of Finnish forests and wood products. Environmental Science and Policy 2: 165-175.

Kasischke, E.S. and L.P. Bruhwiler. 2003. Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. Journal of Geophysical Research 107: 1-14.

Keegan III, C.E., C.E. Fieldler, and T.A. Morgan. 2004. Wildfire in Montana: Potential hazard reduction and economic effects of a strategic treatment program. Forest Products Journal 54(7/8): 21-25.

Keyes, C. and K. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry 17(2): 101-109.

Kline, J.D. 2004. Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the nation's forests. Research Note PNW-RN-542. Corvallis, OR: USDA Forest Service, Pacific Northwest Research Station. 46 p.

Kohlmaier, G., L. Kohlmaier, E. Fries, and W. Jaeschke. 2007. Application of the stock change and the production approach to Harvested Wood Products in the EU-15 countries: a comparative analysis. European Journal of Forest Research 126: 209-223.

Kumar, A., J.B. Cameron, and P.C. Flynn. 2003. Biomass power cost and optimum plant size in western Canada. Biomass & Bioenergy 24(6): 445-464.

Larson, D.S. and R. Mirth. 2004. A case study on the economics of thinning in the wildland-urban interface. Western Journal of Applied Forestry 19(1): 60-65.

Levan-Green, S.L. and J. Livingston. 2001. Exploring the uses for small-diameter trees. Forest Products Journal 51(9): 10-21.

Lim, B., S. Brown, and B. Schlamadinger. 1999. Carbon accounting for forest harvesting and wood products: review and evaluation of different approaches. Environmental Science and Policy 2: 207-216.

Little, J.B. 2003. A light in the forest. American Forests, Winter Issue: 29-32.

Lippke, B., J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Meil. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. Forest Products Journal 54(6): 8-19.

Liski, J., A. Pussinen, K. Pingoud, R. Mäkipää, and T. Karjalainen. 2001. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research 31: 2004-2013.

Luyssaert, S., E. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law, P. Ciais, and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature 455(7210): 213-215.

Lynch, D.L. 2004. What do forest fires really cost? Journal of Forestry 102(6): 42-49.

Malkki, H. and Y. Virtanen. 2003. Selected emissions and efficiencies of energy systems based on logging and sawmill residues. Biomass & Bioenergy 24(4/5): 321-327.

Martin, G.L. and A.R. Ek. 1981. A dynamic programming analysis of silvicultural alternatives for red pine plantation in Wisconsin. Canadian Journal of Forest Research 11: 370 -379.

Masera, O.R., J.F. Garza-Caligaris, M. Kanninen, T. Karjalainen, J. Liski, G.J. Nabuurs, A. Pussinen, B.H.J. de Jong, and G.M.J. Mohren. 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling 164: 177-199.

Mason, C.L., B.R. Lippke, K.W. Zobrist, T.D. Bloxton Jr., K.R. Ceder, J.M. Comnick, J.B. McCarter, and H.K. Rogers. 2006. Investments in fuel removals to avoid forest fires result in substantial benefits. Journal of Forestry 104(1): 27-31.

Matthews, G. 1993. The carbon content of trees. In: Forestry Commission Technical Paper 4, Edinburgh, UK: Forestry Commission.

McArdle, R.E., W.H. Meyer, and D. Bruce. 1961. The yield of Douglas-fir in the Pacific Northwest. US Department of Agriculture Technical Bulletin 201. Washington, D.C. 74 p.

McIver, J.D., P.W. Adams, J.A. Doyal, E.S. Drews, B.R. Hartsough, L.D. Kellogg, C.G. Niwa, R. Ottmar, R. Peck, M. Taratoot, T. Torgersen, and A. Youngblood. 2003. Environmental effects and economics of mechanized logging for fuel reduction in northeastern Oregon mixed-conifer stands. Western Journal of Applied Forestry 18(4): 238-249.

McKenzie, D., Z. Gedalof, D.L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18(4): 890-902.

Miller, R.F., and R.J. Tausch. 2002. The role of fire in juniper and pinyon woodlands: A descriptive analysis. IN Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Misc. Pub. No. 11, Tall Timbers Research Station, Tallahassee, FL. pp. 15-30.

Mitchell, S.R., M.E. Harmon, and K.E.B. O'Connell. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19(3): 642-655.

Nabuurs, G.J. and G.M.J Mohren. 1995. Modelling analysis of potential carbon sequestration in selected forest types. Canadian Journal of Forest Research 25(7): 1157-1172.

Nabuurs, G.J. and R. Sikkema. 2001. International trade in wood products: its role in the land use change and forestry carbon cycle. Climatic Change 49: 377-395.

Nakamura, G. 2004. Biomass thinning for fuel reduction and forest restoration – Issues and opportunities. UC Coop. Extension. http://groups.ucanr.org/forest/.

Niles, J.O. and R. Schwarze. 2001. The value of careful carbon accounting in wood products: Editorial. Climatic Change 49: 371-376.

North, M., M. Hurteau, R. Fiegener, and M. Barbour. 2005. Influence of fire and El Niño on tree recruitment varies by species in Sierran mixed conifer. Forest Science 51(3): 187-197.

North, M., M. Hurteau, and J. Innes. 2009. Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. Ecological Applications 19(6): 1385-1396.

North, M., J. Innes, and H. Zald. 2007. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. Canadian Journal of Forest Research 37(2): 331-342.

Nunery, J.S. and W.S. Keeton. Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products. Forest Ecology and Management 259: 1363-1375.

O'Laughlin, J. and P.S. Cook. 2003. Inventory-based forest health indicators: Implications for national forest management. Journal of Forestry 101(2): 11-17.

Paredes, G. and J.D. Brodie. 1987. Efficient specification and solution of the even-aged rotation and thinning problem. Forest Science 33(1): 14-29.

Perez-Garcia, J., B. Lippke, J. Comnick, and C. Manriquez. 2005. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science 37: 140-148.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as a feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. U.S. Dept. Energy and U.S. Dept. Agriculture http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

Petrova, S., N. Martin, S. Brown, and J. Kadyszewski. 2006. Carbon supply from changes in management of forests, range, and agricultural lands of California: Forest fuel reduction. Winrock International for the California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-093-AD.

Phillips, D.L., S.L. Brown, P.E. Schroeder, and R.A. Birdsey. 2000. Toward error analysis of large-scale forest carbon budgets. Global Ecology and Biogeography 9: 305-313.

Pingoud, K., and F. Wagner. 2006. Methane emissions from landfills and carbon dynamics of harvested wood products: the first-order decay revisited. Mitigation and Adaptation Strategies for Global Change 11: 961-978.

Pingoud, K., B. Schlamadinger, S. Grönkvist, S. Brown, A. Cowie, and G. Marland. 2004. Approaches for inclusion of harvested wood products in future GHG inventories under the UNFCCC, and their consistency with the overall UNFCCC inventory reporting framework. IEA Bioenergy Task 38: Greenhouse Gas Balances of Biomass and Bioenergy Systems. 6 pp.

Pingoud, K. and A. Lehtilä. 2002. Fossil carbon emissions associated with carbon flows of wood products. Mitigation and Adaptation Strategies for Global Change 7: 63-83.

Pingoud, K., A.-L, Perälä, and A. Pussinen. 2001. Carbon dynamics in wood products. Mitigation and Adaptation Strategies for Global Change 6: 91-111.

Reinhardt, E. and L. Holsinger. 2010. Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky Mountains. Forest Ecology and Management 259: 1427-1435.

Richards, K.R. and C. Stokes. 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Climatic Change 63: 1-48.

Ritchie, M.W. and D.W. Hann. 1990. Equations for predicting height growth of six conifer species in southwest Oregon. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. Research Paper 54. 12p.

Ross, S.M. 1983. Introduction to Stochastic Dynamic Programming. Academic Press, Inc. New York, New York. 164 p.

Ruddell, S., R. Sampson, M. Smith, R. Giffen, J. Cathcart, J. Hagan, D. Sosland, J. Godbee, J. Heissenbuttel, S. Lovett, J. Helms, W. Price, and R. Simpson. 2007. The role for sustainably managed forest in climate change mitigation. Journal of Forestry 105(6): 314-319.

Ryan, M.G., M.E. Harmon, R.A. Birdsey, C.P. Giardina, L.S. Heath, R.A. Houghton, R.B. Jackson, D.C. McKinley, J.F. Morrison, B.C. Murray, D.E.Pataki, and K.E. Skog. 2010. A synthesis of the science on forests and carbon for U.S. forests. Issues in Ecology Rep. No. 13. 16 p.

Sampson, R.N. and L.R. Clark. 1996. Wildfire and carbon emissions: A policy modeling approach. Chapter 13 in Forests and Global Change Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. Edited by R.N. Sampson and S. Hair. American Forests Publication; Washington, D.C.

Schmidt, K.M., J.P. Menakis, C.C. Hardy, W.J. Hann, and D.L. Bunnell. 2002. Development of course-scale spatial data for wiland fire and fuel management. Gen. Tech. Rep. RMRS-GTR-87. Fort Collins, CO. USDA Forest Service, Rocky Mountain Research Station. 41 p.

Schoennagel, T., T.T. Veblen, and W.H. Romme. 2004. The interaction of fire, fuels, and climate across the Rocky Mountain forests. BioScience 54(7): 661-676.

Scott, J.H. and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermal's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: USDA, Forest Service, Rocky Mountain Research Station. 72 p.

Sessions, J. 1979. Effects of harvesting technology upon optimal stocking regimes of forest stands in mountainous terrain. Ph.D. thesis, School of Forestry, Oregon State University, Corvallis, Or. 259 p.

Shindler, B., and E. Toman. 2003. Fuel reduction strategies in forest communities: A longitudinal analysis of public support. Journal of Forestry 101(6): 8-15.

Skog, K.E., K. Pingoud, and J.E. Smith. 2004. A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates. Environmental Management 33(S1): 65-73.

Smith, T.F., D.M. Rizzo, and M. North. 2005. Patterns of mortality in an old-growth mixed-conifer forest of the southern Sierra Nevada, California. Forest Science 51(3): 266-275.

Smithwick, E.A.H., M.E. Harmon, S.M. Remillard, S.A. Acker, and J.F. Franklin. 2002. Potential upper bounds of carbon storage in forest of the Pacific Northwest. Ecological Applications 12(5): 1303-1317.

Sohngen, B. and R. Mendelsohn. 2003. An optimal control model of forest carbon sequestration. American Journal of Agricultural Economics 85(2): 448-457.

Solomon, A., R. Birdsey, L. Joyce, and J. Hayes. 2009. Forest service global change research strategy, 2009-2019. USDA Forest Service Research and Development FS-917a. Washington D.C. 20 p.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forest of western Oregon and Washington. Ecology 69(6): 1689-1702.

Stephens, S.L. and J.J. Moghaddas. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215: 21-36.

Stephenson, N.L. 1999. Reference conditions for giant sequoia forest restoration: structure, process, and precision. Ecological Applications 9(4): 1253-1265.

Taylor, A.H. and C.N. Skinner. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management 111: 285-301.

Taylor, A.H. and C.N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structures in the Klamath Mountains. Ecological Applications13(3): 704-719.

Taylor, A.H., V. Trouet, and C.N. Skinner. 2008. Climatic influences on fire regimes in montane forests of the southern Cascades, California, USA. International Journal of Wildland Fire 17: 60-71.

Turner, D.P., W.D. Ritts, B.E. Law, W.B. Cohen, Z. Yang, T. Hudiberg, J.L. Campbell, and M. Duane. 2007. Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. Biogeosciences 4: 597-612.

Vanderberg, M.R., K. Boston, and J. Bailey. 2011. Maximizing carbon storage in the Appalachians: a method for considering the risk of disturbance events. IN: Proceedings of the 17th Central Hardwood Forest Conference. Lexington, KY. April 5-7. U.S. Department of Agriculture, Forest Service, Gen. Tech. Rep.

VCS. 2008. Voluntary Carbon Standard: Tool for AFOLU Non-Permanence Risk Analysis and Buffer Determination. 16 p. www.v-c-s.org

Waltz, A.E.M., P.Z. Fule, W.W. Covington, and M.M. Moore. 2003. Diversity in ponderosa pine structure following ecological restoration treatments. Forest Science 49(6): 885-900.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313(18): 940-943.

Winjum, J.K., S. Brown, and B. Schlamadinger. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. Forest Science 44(2): 272-284.

Winter, G.J., C. Vogt, and J.S. Fried. 2002. Fuel treatments at the wildland-urban interface: Common concerns in diverse regions. Journal of Forestry 100(1): 8-15.

Ximenes, F.A., W.D. Gardner, and A.L. Cowie. 2008. The decomposition of wood products in landfills in Sydney, Australia. Waste Management *In Press* doi:10.1016/j.wasman.2007.11.006

Yoder, J. and K. Blatner. 2004. Incentives and timing of prescribed fire for wildfire risk management. Journal of Forestry 102(6): 38-41.

Zumrawi, A.A. and D.W. Hann. 1989. Height to crown base equations for six tree species in the central western Willamette Valley of Oregon. Oregon State University, Forest Research Laboratory, Research Paper 52. 9p.

Zumrawi, A.A. and D.W. Hann. 1993. Diameter growth equations for Douglas-fir and grand fir in the western Willamette Valley of Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Contribution 4. 6p.

APPENDIX

APPENDIX 1

CFIRE – Forest carbon optimization model: Source Code

```
#include <iostream>
#include <fstream>
#include <cmath>
#include <vector>

using namespace std;

double fbatarget (double xbaa, double xredux);

double fcr (double xht, double xbaa);
double fcarea (double xdbh, double xtrees);
double fcrown (double xheight, double xccfl, double xba, double xdbh);
double ftrees (double xtrees, double xmort);
double fgrowmort (double xdbh, double xcrown, double xsite, double
       xbaad);
double fdinc (double xdbh, double xcrown, double xsite, double xbaad,
       double xba);
double fhinc (double xheight, double xsite);
double fba (double xdbh, double xtrees);
double fbiomass (double xdbh, double xtrees);

double frtrees (double xsdi, int xSDImax);

double fqmd (double xbaa, double xtpa);
double fsdi (double xqmd, double xtpa);
double frd (double xsdi, int xSDImax);
double fsditrees (double xqmd, int xSDImax);

double ftl3 (double xht, double xcr);
double ftu1 (double xht, double xcr);
double ftu5 (double xht, double xcr);
double fsb1 (double xht, double xcr);
double fsb2 (double xht, double xcr);
double fsh4 (double xht, double xcr);
double fsh6 (double xht, double xcr);

double obj_funk (double xbio, double xCf, int xDhorizon, double xUr, double
xUSTd, double xPd, double xCp);

double fire_prob (double xmFRI, int xstage_length);

int main ()
{
       int treat_no = 6; //DEFINE NUMBER OF TREATMENTS (j)
       double redux_incr = 0.15;   //TREATMENT BA REDUCTION INCREMENT
       double site = 90;    //SITE INDEX
       double mFRI = 8;     //(MWDF: 400, DMDF: 80, MCME: 8)
```

```
double Ur = 0.66;
double USTd = 0.75;
double Pd = 0.01;
double Cf = 0.50;
int Dhorizon;
int stage_length = 10;
int stage_no;
int decay_horizon = 10;
double decay_mort = 0.029;
double release_fmort = 0.048;
int SDImax = 525;
const signed int endofrecord = -1;
int eomegarec;

double redux;

int scan_prev_stg_st;
int st, scan_st;
int scan_j;
int fire, scan_fire;
double baa, scan_baa;
double bio, scan_bio;
double sdi, scan_sdi;
double ccf, scan_ccf;
double removal, scan_removal;
double delta_bio, scan_delta_bio;
double removal_bio, scan_removal_bio;
double mort_bio, scan_mort_bio;
double fmort_bio, scan_fmort_bio;

double qmd;
double ht;
double cr;
double tpa;
double rd;
double sdi_tpa;
double sdi_qmd;

int species;
double dbh, scan_dbh;
double trees, scan_trees;
double height, scan_height;
double ba, scan_ba;

double baad;
double biomass;
double crown;
double pmort;
double fmort;
double removal_biomass;
double mort_trees, mort_biomass;
double fmort_trees, fmort_biomass;
double basum;
double htsum;
double baatarg;
double carea, sccarea;
double ccfl;
double batarg;
```

```
        double treestarg;
        double sdi_treestarg;

        int rspecies = 202;
        double rdbh = 2;
        double rtrees;
        double rheight = 15;
        double rba;

        int prev_stg_st, scan_prev_stg_st_1, scan_prev_stg_st_2,
               scan_Cprev_stg_st, scan_Cprev_stg_st_1;
        int state, scan_st_1, scan_Cst, scan_Cst_1;
        int j, scan_j_1, scan_Cj, scan_Cj_1;
        int scan_fire_1;
        double scan_baa_1;
        double scan_bio_1;
        double scan_sdi_1;
        double scan_ccf_1;
        double scan_removal_1, scan_Cremoval, scan_Cremoval_1;
        double scan_delta_bio_1;
        double scan_removal_bio_1, scan_Cremoval_bio, scan_Cremoval_bio_1;
        double scan_mort_bio_1;
        double scan_fmort_bio_1;

        double C, C_1, Cp, scan_Cp, scan_Cp_1, CCC, CCCmax;

        double P_fire;

        P_fire = fire_prob(mFRI, stage_length);

        FILE *stand1;
        FILE *stand2;
        FILE *tree1;
        FILE *tree2;
        fpos_t pos;
        fpos_t pos1;
        FILE *C1;
        FILE *C2;
        FILE *C99;

//START: STAGE 0 operations | READ IN INITIAL TEXT FILES

        fopen_s (&stand2, "stage_0.txt", "a+");

//INPUT STANDFILE OPERATION
        fopen_s (&stand1, "stand_xx.txt", "r+");

        fscanf_s (stand1, "%lf %lf %lf %lf", &qmd, &ht, &scan_baa, &tpa);
        fclose(stand1);

        st = 0;
        ccf = 0;
        bio = 0;

        cr = fcr(ht, scan_baa);
        sdi = fsdi(qmd, tpa);

        fopen_s (&tree2, "treelist_0.txt", "a+");
```

```
//INPUT TREEFILE OPERATION
	fopen_s (&tree1, "tree_xx.txt", "r+");

	while (!feof (tree1))
	{
		fscanf_s (tree1, "%i %lf %lf %lf %lf", &species, &scan_dbh,
			&scan_trees, &scan_height, &scan_ba);

		fprintf_s (tree2, "\n %i %i %lf %lf %lf %lf", st, species,
			scan_dbh, scan_trees, scan_height, scan_ba);

		carea = fcarea(scan_dbh, scan_trees);
		ccf = ccf + carea;
		biomass = fbiomass(scan_dbh, scan_trees);
		bio = bio + biomass; //Sum biomass for treelist

	}
	fclose(tree1);
	fprintf_s (stand2, "\n %i %lf %lf %lf %lf", st, scan_baa, bio, sdi,
		ccf);

//STAGE 0 to 1 operations
	fopen_s (&stand1, "stage_1.txt", "a+");
	rewind (stand2);
	fopen_s (&tree1, "treelist_1.txt", "a+");
	rewind (tree2);
	fscanf_s (stand2, "%i %lf %lf %lf %lf", &scan_prev_stg_st, &scan_baa,
		&scan_bio, &scan_sdi, &scan_ccf);
	fclose(stand2);

	sdi_tpa = 0;
	redux = 0;
	st = 0;
	vector< vector<double> > treev;

	while (!feof (tree2))
	{
		fscanf_s (tree2, "%i %i %lf %lf %lf %lf", &scan_prev_stg_st,
			&species, &scan_dbh, &scan_trees, &scan_height, &scan_ba);

		sdi_tpa = sdi_tpa + scan_trees;
		vector<double> row(5);
		row[0] = species;
		row[1] = scan_dbh;
		row[2] = scan_trees;
		row[3] = scan_height;
		row[4] = scan_ba;
		treev.push_back(row);
	}
	fclose(tree2);

	for (int j = 0; j < treat_no; j++)
	{
		fire = 0;
		baatarg = fbatarget(scan_baa, redux);
		removal = scan_baa - baatarg;
		bio = 0;
```

```
                removal_bio = 0;
                mort_bio = 0;
                fmort_bio = 0;
                basum = 0;
                baa = 0;
                tpa = 0;
                htsum = 0;
                baad = scan_baa;
                ccf = 0;
                ccfl = scan_ccf;
                int i = 0;

//REGENERATION
                rtrees = frtrees(scan_sdi, SDImax);
                if (rtrees > 0)
                {
                        rba = fba(rdbh, rtrees);
                        fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
                                rspecies, rdbh, rtrees, rheight, rba);

                        biomass = fbiomass(rdbh, rtrees);
                        bio = bio + biomass;
                        htsum = htsum + rheight;
                        tpa = tpa + rtrees;
                        baa = baa + rba;
                        carea = fcarea(rdbh, rtrees);
                        ccf = ccf + carea;
                }
//END Regeneration

                for (int k = 0; k < static_cast <double> (treev.size()); k++)
                {
                        baad = baad - treev[k][4];
                        sccarea = fcarea(treev[k][1], treev[k][2]);
                        ccfl = ccfl - sccarea;
                        basum = treev[k][4] + basum;

                        if (removal == 0)
                        {
                                i = i + 1;
                                species = static_cast <int> (treev[k][0]);
                                crown = fcrown(treev[k][3], ccfl, treev[k][4],
                                        treev[k][1]);
                                pmort = fgrowmort(treev[k][1], crown, site, baad);

                                if (scan_sdi > SDImax)
                                {
                                        sdi_qmd = fqmd(scan_baa, sdi_tpa);
                                        sdi_treestarg = fsditrees(sdi_qmd, SDImax);

                                        pmort = pmort + ((sdi_tpa - sdi_treestarg) /
                                                sdi_tpa);
                                }
                                else pmort = pmort;

                                trees = ftrees(treev[k][2], pmort);
                                dbh = fdinc(treev[k][1], crown, site, baad,
                                        treev[k][4]);
```

```
        height = fhinc(treev[k][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        mort_trees = treev[k][2] - trees;
        mort_biomass = fbiomass(treev[k][1], mort_trees);
        carea = fcarea(dbh, trees);

        fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
               species, dbh, trees, height, ba);

        bio = bio + biomass;
        htsum = htsum + height;
        tpa = tpa + trees;
        baa = baa + ba;
        ccf = ccf + carea;
        mort_bio = mort_bio + mort_biomass;
}
if (basum <= removal)
{
        removal_biomass = fbiomass(treev[k][1] ,
               treev[k][2]) * exp (-0.3737 - (1.8055 /
               treev[k][1]));
        removal_bio = removal_bio + removal_biomass;
}
if (basum > removal && removal > 0 && i == 0)
{
        batarg = basum - removal;
        treestarg = (batarg / treev[k][4]) * treev[k][2];
        i = i + 1;
        species = static_cast <int> (treev[k][0]);
        crown = fcrown(treev[k][3], ccfl, treev[k][4] –
               batarg, treev[k][1]);
        pmort = fgrowmort(treev[k][1], crown, site, baad);
        trees = ftrees(treestarg, pmort);
        dbh = fdinc(treev[k][1], crown, site, baad,
               treev[k][4] - batarg);
        height = fhinc(treev[k][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        removal_biomass = fbiomass(treev[k][1], treev[k][2]
               - treestarg) * exp (-0.3737 - (1.8055 /
               treev[k][1]));
        mort_trees = treestarg - trees;
        mort_biomass = fbiomass(treev[k][1], mort_trees);
        carea = fcarea(dbh, trees);

        fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
               species, dbh, trees, height, ba);

        bio = bio + biomass;
        htsum = htsum + height;
        tpa = tpa + trees;
        baa = baa + ba;
        ccf = ccf + carea;
        removal_bio = removal_bio + removal_biomass;
        mort_bio = mort_bio + mort_biomass;
}
else if (basum > removal && removal > 0)
```

```
				{
					i = i + 1;

					species = static_cast <int> (treev[k][0]);
					crown = fcrown(treev[k][3], ccfl, treev[k][4],
						treev[k][1]);
					pmort = fgrowmort(treev[k][1], crown, site, baad);
					trees = ftrees(treev[k][2], pmort);
					dbh = fdinc(treev[k][1], crown, site, baad,
						treev[k][4]);
					height = fhinc(treev[k][3], site);
					ba = fba(dbh, trees);
					biomass = fbiomass(dbh, trees);
					mort_trees = treev[k][2] - trees;
					mort_biomass = fbiomass(treev[k][1], mort_trees);
					carea = fcarea(dbh, trees);

					fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
						species, dbh, trees, height, ba);

					bio = bio + biomass;
					htsum = htsum + height;
					tpa = tpa + trees;
					baa = baa + ba;
					ccf = ccf + carea;
					mort_bio = mort_bio + mort_biomass;
				}
			}

			if (rtrees > 0)
			{
				i = i + 1;
			}

			ht = htsum / i;
			cr = fcr(ht, baa);
			qmd = fqmd(baa, tpa);
			sdi = fsdi(qmd, tpa);
			delta_bio = bio - scan_bio;
			mort_bio = mort_bio * (1 - decay_mort * decay_horizon);
			bio = bio + mort_bio;

			fprintf_s (tree1, "\n %i", endofrecord);
			fprintf_s (stand1, "\n %i %i %i %i %lf %lf %lf %lf %lf %lf %lf
				%lf %lf", scan_prev_stg_st, st, j, fire, baa, bio, sdi,
				ccf, removal, delta_bio, removal_bio, mort_bio,
				fmort_bio);

			st = st + 1;
			fire = 1;
			rd = frd(sdi, SDImax);

//FIRE BEHAVIOR FUEL MODEL  DECISION ALGORITHM

			if (j == 0)	//If undisturbed (no treatment, no fire)
			{
				if (rd >= 0.4)		//If Density Class = 4-5
				{
```

```
					if (qmd > 5)
					{
						fmort = ftl3(ht, cr);
					}
					else fmort = fsh4(ht, cr);
				}
				else	//If relative density < 0.4, Density Class = 2-3
				{
					if (qmd > 9)
					{
						fmort = fsb1(ht, cr);
					}
					else if (qmd <= 5)
					{
						fmort = ftu5(ht, cr);
					}
					else fmort = fsh4(ht, cr);
				}
			}
			else //Else, if disturbed (treatment, fire)
			{
				if (rd >= 0.4)		//If Density Class = 4-5
				{
					if (qmd > 5)
					{
						fmort = ftu1(ht, cr);
					}
					else fmort = fsh6(ht, cr);
				}
				else //If relative density < 0.4, Density Class = 2-3
				{
					if (qmd > 9)
					{
						fmort = fsb2(ht, cr);
					}
					else if (qmd <= 5)
					{
						fmort = fsh5(ht, cr);
					}
					else fmort = fsh6(ht, cr);
				}
			}
	//END FBFM DECISION ALGORITHM

			if (fmort > 0)
			{
				bio = 0;
				removal_bio = 0;
				mort_bio = 0;
				fmort_bio = 0;
				basum = 0;
				baa = 0;
				tpa = 0;
				baad = scan_baa;
				ccf = 0;
				ccfl = scan_ccf;
				i = 0;
```

```
//REGENERATION

                    rtrees = frtrees(scan_sdi, SDImax) * (1 - fmort);

                    if (rtrees > 0)
                    {
                           rba = fba(rdbh, rtrees);

                           fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
                                  rspecies, rdbh, rtrees, rheight, rba);

                           biomass = fbiomass(rdbh, rtrees);
                           bio = bio + biomass;
                           tpa = tpa + rtrees;
                           baa = baa + rba;
                           carea = fcarea(rdbh, rtrees);
                           ccf = ccf + carea;
                    }
//END Regeneration

                    for (int m = 0; m < static_cast <double> (treev.size());
                           m++)
                    {
                           baad = baad - treev[m][4];
                           sccarea = fcarea(treev[m][1], treev[m][2]);
                           ccfl = ccfl - sccarea;
                           basum = treev[m][4] + basum;

                           if (removal == 0)
                           {
                                  i = i + 1;

                                  species = static_cast <int> (treev[m][0]);
                                  crown = fcrown(treev[m][3], ccfl,
                                         treev[m][4], treev[m][1]);
                                  pmort = fgrowmort(treev[m][1], crown, site,
                                         baad) + fmort;

                                  if (scan_sdi > SDImax)
                                  {
                                         sdi_qmd = fqmd(scan_baa, sdi_tpa);
                                         sdi_treestarg = fsditrees(sdi_qmd,
                                                SDImax);

                                         pmort = pmort + ((sdi_tpa –
                                                sdi_treestarg) / sdi_tpa);
                                  }
                                  else pmort = pmort;

                                  if (pmort <= 1)
                                  {
                                         pmort = pmort;
                                  }
                                  else pmort = 1;

                                  trees = ftrees(treev[m][2], pmort);
                                  dbh = fdinc(treev[m][1], crown, site, baad,
                                         treev[m][4]);
```

```
            height = fhinc(treev[m][3], site);
            ba = fba(dbh, trees);
            biomass = fbiomass(dbh, trees);
            fmort_trees = ftrees(treev[m][2], 1 –
                   fmort);
            fmort_biomass = fbiomass(treev[m][1],
                   fmort_trees);

            mort_trees = (treev[m][2] - trees) –
                   fmort_trees;
            mort_biomass = fbiomass(treev[m][1],
                   mort_trees);
            carea = fcarea(dbh, trees);

            fprintf_s (tree1, "\n %i %i %lf %lf %lf
                   %lf", st, species, dbh, trees,
                   height, ba);

            bio = bio + biomass;
            htsum = htsum + height;
            tpa = tpa + trees;
            baa = baa + ba;
            ccf = ccf + carea;
            mort_bio = mort_bio + mort_biomass;
            fmort_bio = fmort_bio + fmort_biomass;
     }
     if (basum <= removal)
     {
            removal_biomass = fbiomass(treev[m][1],
            treev[m][2]) * exp (-0.3737 - (1.8055 /
            treev[m][1]));
            removal_bio = removal_bio + removal_biomass;
     }
     if (basum > removal && removal > 0 && i == 0)
     {
            batarg = basum - removal;
            treestarg = (batarg / treev[m][4]) *
                   treev[m][2];

            i = i + 1;

            species = static_cast <int> (treev[m][0]);
            crown = fcrown(treev[m][3], ccfl,
                   treev[m][4] - batarg, treev[m][1]);
            pmort = fgrowmort(treev[m][1], crown, site,
                   baad) + fmort;

            if (pmort <= 1)
            {
                   pmort = pmort;
            }
            else pmort = 1;

            trees = ftrees(treestarg, pmort);
            dbh = fdinc(treev[m][1], crown, site, baad,
                   treev[m][4] - batarg);
            height = fhinc(treev[m][3], site);
            ba = fba(dbh, trees);
```

```
			biomass = fbiomass(dbh, trees);
			removal_biomass = fbiomass(treev[m][1],
				treev[m][2] - treestarg) * exp (-
				0.3737 - (1.8055 / treev[m][1]));
			fmort_trees = ftrees(treestarg, 1 - fmort);
			fmort_biomass = fbiomass(treev[m][1],
				fmort_trees);

			mort_trees = (treestarg - trees) –
				fmort_trees;
			mort_biomass = fbiomass(treev[m][1],
				mort_trees);
			carea = fcarea(dbh, trees);

			fprintf_s (tree1, "\n %i %i %lf %lf %lf
				%lf", st, species, dbh, trees,
				height, ba);

			bio = bio + biomass;
			htsum = htsum + height;
			tpa = tpa + trees;
			baa = baa + ba;
			ccf = ccf + carea;
			removal_bio = removal_bio + removal_biomass;
			mort_bio = mort_bio + mort_biomass;
			fmort_bio = fmort_bio + fmort_biomass;
		}
		else if (basum > removal && removal > 0)
		{
			i = i + 1;

			species = static_cast <int> (treev[m][0]);
			crown = fcrown(treev[m][3], ccfl,
				treev[m][4], treev[m][1]);
			pmort = fgrowmort(treev[m][1], crown, site,
				baad) + fmort;

			if (pmort <= 1)
			{
				pmort = pmort;
			}
			else pmort = 1;

			trees = ftrees(treev[m][2], pmort);
			dbh = fdinc(treev[m][1], crown, site, baad,
				treev[m][4]);
			height = fhinc(treev[m][3], site);
			ba = fba(dbh, trees);
			biomass = fbiomass(dbh, trees);
			fmort_trees = ftrees(treev[m][2], 1 –
				fmort);
			fmort_biomass = fbiomass(treev[m][1],
				fmort_trees);
			mort_trees = (treev[m][2] - trees) –
				fmort_trees;
			mort_biomass = fbiomass(treev[m][1],
				mort_trees);
			carea = fcarea(dbh, trees);
```

```
                        fprintf_s (tree1, "\n %i %i %lf %lf %lf
                               %lf", st, species, dbh, trees,
                               height, ba);

                        bio = bio + biomass;
                        htsum = htsum + height;
                        tpa = tpa + trees;
                        baa = baa + ba;
                        ccf = ccf + carea;
                        mort_bio = mort_bio + mort_biomass;
                        fmort_bio = fmort_bio + fmort_biomass;
                    }
                }

                qmd = fqmd(baa, tpa);
                sdi = fsdi(qmd, tpa);
                mort_bio = mort_bio * (1 - decay_mort * decay_horizon);
                fmort_bio = fmort_bio * (1 - release_fmort);
                bio = bio + mort_bio + fmort_bio;
                delta_bio = bio - scan_bio;

                fprintf_s (tree1, "\n %i", endofrecord);
                fprintf_s (stand1, "\n %i %i %i %i %lf %lf %lf %lf %lf %lf
                       %lf %lf %lf", scan_prev_stg_st, st, j, fire, baa,
                       bio, sdi, ccf, removal, delta_bio, removal_bio,
                       mort_bio, fmort_bio);

                st = st + 1;
            }

            redux = redux + redux_incr;

            if (scan_sdi <= SDImax * 0.1)
            {
                break;
            }

        }

    //STAGE 1 to 2 operations

        fopen_s (&stand2, "stage_2.txt", "a+");
        rewind (tree1);

        fopen_s (&tree2, "treelist_2.txt", "a+");
        rewind (stand1);

        st = 0;

        while (!feof (stand1))
        {
            fscanf_s (stand1, "%i %i %i %i %lf %lf %lf %lf %lf %lf %lf %lf
                   %lf", &scan_prev_stg_st, &scan_st, &scan_j, &scan_fire,
                   &scan_baa, &scan_bio, &scan_sdi, &scan_ccf, &scan_removal,
                   &scan_delta_bio, &scan_removal_bio, &scan_mort_bio,
                   &scan_fmort_bio);
```

```
        sdi_tpa = 0;
        redux = 0;

        vector< vector<double> > treev;

        fgetpos (tree1, &pos);

        goto label_1;

label_1: fsetpos (tree1, &pos);
        fscanf_s (tree1, "%i", &eomegarec);

        if (eomegarec >= 0)
        {
                fscanf_s (tree1, "%i %lf %lf %lf %lf", &species,
                        &scan_dbh, &scan_trees, &scan_height, &scan_ba);

                sdi_tpa = sdi_tpa + scan_trees;

                vector<double> row(5);

                row[0] = species;
                row[1] = scan_dbh;
                row[2] = scan_trees;
                row[3] = scan_height;
                row[4] = scan_ba;

                treev.push_back(row);

                fscanf_s (tree1, "\n");
                fgetpos (tree1, &pos);
                goto label_1;
        }
        else
        {
                fscanf_s (tree1, "\n");
                fgetpos (tree1, &pos);
                goto label_2;
        }

label_2: for (int j = 0; j < treat_no; j++)
        {
                fire = 0;
                baatarg = fbatarget(scan_baa, redux);
                removal = scan_baa - baatarg;

                bio = 0;
                removal_bio = 0;
                mort_bio = 0;
                fmort_bio = 0;
                basum = 0;
                baa = 0;
                tpa = 0;
                htsum = 0;
                baad = scan_baa;
                ccf = 0;
                ccfl = scan_ccf;
```

```
                    int i = 0;

//REGENERATION
                    rtrees = frtrees(scan_sdi, SDImax);

                    if (rtrees > 0)
                    {
                           rba = fba(rdbh, rtrees);


                           fprintf_s (tree2, "\n %i %i %lf %lf %lf %lf", st,
                                  rspecies, rdbh, rtrees, rheight, rba);

                           biomass = fbiomass(rdbh, rtrees);
                           bio = bio + biomass;
                           htsum = htsum + rheight;
                           tpa = tpa + rtrees;
                           baa = baa + rba;
                           carea = fcarea(rdbh, rtrees);
                           ccf = ccf + carea;
                    }
//END Regeneration

                    for (int k = 0; k < static_cast <double> (treev.size());
                           k++)
                    {
                           baad = baad - treev[k][4];
                           sccarea = fcarea(treev[k][1], treev[k][2]);
                           ccfl = ccfl - sccarea;
                           basum = treev[k][4] + basum;

                           if (removal == 0)
                           {
                                  i = i + 1;

                                  species = static_cast <int> (treev[k][0]);
                                  crown = fcrown(treev[k][3], ccfl,
                                         treev[k][4], treev[k][1]);
                                  pmort = fgrowmort(treev[k][1], crown, site,
                                         baad);

                                  if (scan_sdi > SDImax)
                                  {
                                         sdi_qmd = fqmd(scan_baa, sdi_tpa);
                                         sdi_treestarg = fsditrees(sdi_qmd,
                                                SDImax);
                                         pmort = pmort + ((sdi_tpa –
                                                sdi_treestarg) / sdi_tpa);
                                  }
                                  else pmort = pmort;

                                  trees = ftrees(treev[k][2], pmort);
                                  dbh = fdinc(treev[k][1], crown, site, baad,
                                         treev[k][4]);
                                  height = fhinc(treev[k][3], site);
                                  ba = fba(dbh, trees);
                                  biomass = fbiomass(dbh, trees);
                                  mort_trees = treev[k][2] - trees;
```

```
		mort_biomass = fbiomass(treev[k][1],
			mort_trees);
		carea = fcarea(dbh, trees);

		fprintf_s (tree2, "\n %i %i %lf %lf %lf
			%lf", st, species, dbh, trees,
			height, ba);

		bio = bio + biomass;
		htsum = htsum + height;
		tpa = tpa + trees;
		baa = baa + ba;
		ccf = ccf + carea;
		mort_bio = mort_bio + mort_biomass;
	}
	if (basum <= removal)
	{
		removal_biomass = fbiomass(treev[k][1],
			treev[k][2]) * exp (-0.3737 - (1.8055
			/ treev[k][1]));
		removal_bio = removal_bio + removal_biomass;
	}
	if (basum > removal && removal > 0 && i == 0)
	{
		batarg = basum - removal;
		treestarg = (batarg / treev[k][4]) *
			treev[k][2];

		i = i + 1;

		species = static_cast <int> (treev[k][0]);
		crown = fcrown(treev[k][3], ccfl,
			treev[k][4] - batarg, treev[k][1]);
		pmort = fgrowmort(treev[k][1], crown, site,
			baad);
		trees = ftrees(treestarg, pmort);
		dbh = fdinc(treev[k][1], crown, site, baad,
			treev[k][4] - batarg);
		height = fhinc(treev[k][3], site);
		ba = fba(dbh, trees);
		biomass = fbiomass(dbh, trees);
		removal_biomass = fbiomass(treev[k][1],
			treev[k][2] - treestarg) * exp (-
			0.3737 - (1.8055 / treev[k][1]));
		mort_trees = treestarg - trees;
		mort_biomass = fbiomass(treev[k][1],
			mort_trees);
		carea = fcarea(dbh, trees);

		fprintf_s (tree2, "\n %i %i %lf %lf %lf
			%lf", st, species, dbh, trees,
			height, ba);

		bio = bio + biomass;
		htsum = htsum + height;
		tpa = tpa + trees;
		baa = baa + ba;
		ccf = ccf + carea;
```

```
                removal_bio = removal_bio + removal_biomass;
                mort_bio = mort_bio + mort_biomass;
        }
        else if (basum > removal && removal > 0)
        {
                i = i + 1;

                species = static_cast <int> (treev[k][0]);
                crown = fcrown(treev[k][3], ccfl,
                        treev[k][4], treev[k][1]);
                pmort = fgrowmort(treev[k][1], crown, site,
                        baad);
                trees = ftrees(treev[k][2], pmort);
                dbh = fdinc(treev[k][1], crown, site, baad,
                        treev[k][4]);
                height = fhinc(treev[k][3], site);
                ba = fba(dbh, trees);
                biomass = fbiomass(dbh, trees);
                mort_trees = treev[k][2] - trees;
                mort_biomass = fbiomass(treev[k][1],
                        mort_trees);
                carea = fcarea(dbh, trees);

                fprintf_s (tree2, "\n %i %i %lf %lf %lf
                        %lf", st, species, dbh, trees,
                        height, ba);

                bio = bio + biomass;
                htsum = htsum + height;
                tpa = tpa + trees;
                baa = baa + ba;
                ccf = ccf + carea;
                mort_bio = mort_bio + mort_biomass;
        }
}

if (rtrees > 0)
{
        i = i + 1;
}

ht = htsum / i;
cr = fcr(ht, baa);
qmd = fqmd(baa, tpa);
sdi = fsdi(qmd, tpa);
mort_bio = (mort_bio  + scan_mort_bio) * (1 - decay_mort *
        decay_horizon);
bio = bio + mort_bio;
delta_bio = bio - scan_bio;

fprintf_s (tree2, "\n %i", endofrecord);
fprintf_s (stand2, "\n %i %i %i %i %lf %lf %lf %lf %lf %lf
        %lf %lf %lf", scan_st, st, j, fire, baa, bio, sdi,
        ccf,removal, delta_bio, removal_bio, mort_bio,
        fmort_bio);

st = st + 1;
fire = 1;
```

```
                    rd = frd(sdi, SDImax);

//FIRE BEHAVIOR FUEL MODEL  DECISION ALGORITHM
                    if (j + scan_fire > 0)
                    {
                           if (rd >= 0.4)
                           {
                                  if (qmd > 5)
                                  {
                                         fmort = 0;
                                  }
                                  else fmort = fsh6(ht, cr);
                           }
                           else
                           {
                                  if (qmd > 9)
                                  {
                                         fmort = fsb2(ht, cr);
                                  }
                                  else if (qmd <= 5)
                                  {
                                         fmort = 0.98;
                                  }
                                  else fmort = fsh6(ht, cr);
                           }
                    }
                    else //Else, if undisturbed
                    {
                           if (rd >= 0.4)       //Density class 4-5
                           {
                                  if (qmd > 5)
                                  {
                                         fmort = 0;
                                  }
                                  else fmort = fsh4(ht, cr);
                           }
                           else   //Density class 2-3
                           {
                                  if (qmd > 9)
                                  {
                                         fmort = fsb1(ht, cr);
                                  }
                                  else if (qmd <= 5)
                                  {
                                         fmort = ftu5(ht, cr);
                                  }
                                  else fmort = fsh4(ht, cr);
                           }
                    }
//END FBFM DECISION ALGORITHM

                    if (fmort > 0)
                    {

                           bio = 0;
                           removal_bio = 0;
                           mort_bio = 0;
                           fmort_bio = 0;
```

```
                                basum = 0;
                                baa = 0;
                                tpa = 0;
                                baad = scan_baa;
                                ccf = 0;
                                ccfl = scan_ccf;

                                i = 0;

//REGENERATION
                                rtrees = frtrees(scan_sdi, SDImax) * (1 - fmort);

                                if (rtrees > 0)
                                {
                                        rba = fba(rdbh, rtrees);

                                        fprintf_s (tree2, "\n %i %i %lf %lf %lf
                                                %lf", st, rspecies, rdbh, rtrees,
                                                rheight, rba);

                                        biomass = fbiomass(rdbh, rtrees);
                                        bio = bio + biomass;
                                        tpa = tpa + rtrees;
                                        baa = baa + rba;
                                        carea = fcarea(rdbh, rtrees);
                                        ccf = ccf + carea;
                                }
//END Regeneration

                                for (int m = 0; m < static_cast <double>
                                        (treev.size()); m++)
                                {
                                        baad = baad - treev[m][4];
                                        sccarea = fcarea(treev[m][1], treev[m][2]);
                                        ccfl = ccfl – sccarea;
                                        basum = treev[m][4] + basum;

                                        if (removal == 0)
                                        {
                                                i = i + 1;

                                                species = static_cast <int>
                                                        (treev[m][0]);
                                                crown = fcrown(treev[m][3], ccfl,
                                                        treev[m][4], treev[m][1]);
                                                pmort = fgrowmort(treev[m][1], crown,
                                                        site, baad) + fmort;

                                                if (scan_sdi > SDImax)
                                                {
                                                        sdi_qmd = fqmd(scan_baa,
                                                                sdi_tpa);
                                                        sdi_treestarg =
                                                                fsditrees(sdi_qmd,
                                                                SDImax);


                                                        pmort = pmort + ((sdi_tpa –
```

```
                        sdi_treestarg) /
                        sdi_tpa);
        }
        else pmort = pmort;

        if (pmort <= 1)
        {
                pmort = pmort;
        }
        else pmort = 1;

        trees = ftrees(treev[m][2], pmort);
        dbh = fdinc(treev[m][1], crown, site,
                baad, treev[m][4]);
        height = fhinc(treev[m][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        fmort_trees = ftrees(treev[m][2], 1 –
                fmort);
        fmort_biomass = fbiomass(treev[m][1],
                fmort_trees);

        mort_trees = (treev[m][2] - trees) –
                fmort_trees;
        mort_biomass = fbiomass(treev[m][1],
                mort_trees);
        carea = fcarea(dbh, trees);

        fprintf_s (tree2, "\n %i %i %lf %lf
                %lf %lf", st, species, dbh,
                trees, height, ba);

        bio = bio + biomass;
        htsum = htsum + height;
        tpa = tpa + trees;
        baa = baa + ba;
        ccf = ccf + carea;
        mort_bio = mort_bio + mort_biomass;
        fmort_bio = fmort_bio +
                fmort_biomass;
}
if (basum <= removal)
{
        removal_biomass =
                fbiomass(treev[m][1],
                treev[m][2]) * exp (-0.3737 –
                (1.8055 / treev[k][1]));
        removal_bio = removal_bio +
                removal_biomass;
}
if (basum > removal && removal > 0 && i ==
        0)
{
        batarg = basum - removal;
        treestarg = (batarg / treev[m][4]) *
                treev[m][2];

        i = i + 1;
```

```
		species = static_cast <int>
			(treev[m][0]); //Constant
		crown = fcrown(treev[m][3], ccfl,
			treev[m][4] - batarg,
			treev[m][1]);
		pmort = fgrowmort(treev[m][1], crown,
			site, baad) + fmort;

		if (pmort <= 1)
		{
			pmort = pmort;
		}
		else pmort = 1;

		trees = ftrees(treestarg, pmort);
		dbh = fdinc(treev[m][1], crown, site,
			baad, treev[m][4] - batarg);
		height = fhinc(treev[m][3], site);
		ba = fba(dbh, trees);
		biomass = fbiomass(dbh, trees);
		removal_biomass =
			fbiomass(treev[m][1],
			treev[m][2] – treestarg) * exp
			(-0.3737 – (1.8055 /
			treev[m][1]));
		fmort_trees = ftrees(treestarg, 1 –
			fmort);
		fmort_biomass = fbiomass(treev[m][1],
			fmort_trees);
		mort_trees = (treestarg - trees) –
			fmort_trees;
		mort_biomass = fbiomass(treev[m][1],
			mort_trees);
		carea = fcarea(dbh, trees);

		fprintf_s (tree2, "\n %i %i %lf %lf
			%lf %lf", st, species, dbh,
			trees, height, ba);

		bio = bio + biomass;
		htsum = htsum + height;
		tpa = tpa + trees;
		baa = baa + ba;
		ccf = ccf + carea;
		removal_bio = removal_bio +
			removal_biomass;
		mort_bio = mort_bio + mort_biomass;
		fmort_bio = fmort_bio +
			fmort_biomass;
	}
	else if (basum > removal && removal > 0)
	{
		i = i + 1;

		species = static_cast <int>
			(treev[m][0]); //Constant
		crown = fcrown(treev[m][3], ccfl,
```

```
                            treev[m][4], treev[m][1]);
                     pmort = fgrowmort(treev[m][1], crown,
                            site, baad) + fmort;

                     if (pmort <= 1)
                     {
                            pmort = pmort;
                     }
                     else pmort = 1;

                     trees = ftrees(treev[m][2], pmort);
                     dbh = fdinc(treev[m][1], crown, site,
                            baad, treev[m][4]);
                     height = fhinc(treev[m][3], site);
                     ba = fba(dbh, trees);
                     biomass = fbiomass(dbh, trees);
                     fmort_trees = ftrees(treev[m][2], 1 –
                            fmort);
                     fmort_biomass = fbiomass(treev[m][1],
                            fmort_trees);
                     mort_trees = (treev[m][2] - trees) –
                            fmort_trees;
                     mort_biomass = fbiomass(treev[m][1],
                            mort_trees);
                     carea = fcarea(dbh, trees);

                     fprintf_s (tree2, "\n %i %i %lf %lf
                            %lf %lf", st, species, dbh,
                            trees, height, ba);

                     bio = bio + biomass;
                     htsum = htsum + height;
                     tpa = tpa + trees;
                     baa = baa + ba;
                     ccf = ccf + carea;
                     mort_bio = mort_bio + mort_biomass;
                     fmort_bio = fmort_bio +
                            fmort_biomass;
              }
       }

       qmd =fqmd(baa, tpa);
       sdi = fsdi(qmd, tpa);
       mort_bio = (mort_bio + scan_mort_bio) * (1 –
              decay_mort * decay_horizon);
       fmort_bio = fmort_bio * (1 - release_fmort) +
              (scan_fmort_bio * (1 - decay_mort *
              decay_horizon));
       bio = bio + mort_bio + fmort_bio;
       delta_bio = bio - scan_bio;

       fprintf_s (tree2, "\n %i", endofrecord);
       fprintf_s (stand2, "\n %i %i %i %i %lf %lf %lf %lf
              %lf %lf %lf %lf %lf", scan_st, st, j, fire,
              baa, bio, sdi, ccf, removal, delta_bio,
              removal_bio, mort_bio, fmort_bio);

       st = st + 1;
```

```
				}
				redux = redux + redux_incr;

				if (scan_sdi <= SDImax * 0.1)
				{
					break;
				}
			}
		}
		fclose(tree1);
		fclose(stand1);

	//START STAGE 2 to 3 operations

		fopen_s (&stand1, "stage_3.txt", "a+");
		rewind (stand2);
		fopen_s (&tree1, "treelist_3.txt", "a+");
		rewind (tree2);

		//return stage 3 output//

		fclose(tree2);
		fclose(stand2);

	//START STAGE 3 to 4 operations

		fopen_s (&stand2, "stage_4.txt", "a+");
		rewind (stand1);
		fopen_s (&tree2, "treelist_4.txt", "a+");
		rewind (tree1);

		//return stage 4 output//

		fclose(tree1);
		fclose(stand1);

	//START STAGE 4 to 5 operations

		fopen_s (&stand1, "stage_5.txt", "a+");
		rewind (stand2);
		fopen_s (&tree1, "treelist_5.txt", "a+");
		rewind (tree2);

		//return stage 5 output//

		fclose(tree2);
		fclose(stand2);

	//START STAGE 5 to 6 operations

		fopen_s (&stand2, "stage_6.txt", "a+");
		rewind (stand1);
		fopen_s (&tree2, "treelist_6.txt", "a+");
		rewind (tree1);

		//return stage 6 output//

		fclose(tree1);
```

```
        fclose(stand1);

//START STAGE 6 to 7 operations

        fopen_s (&stand1, "stage_7.txt", "a+");
        rewind (stand2);
        fopen_s (&tree1, "treelist_7.txt", "a+");
        rewind (tree2);
        cout << "State Space 7: " << st << endl;

        fclose(tree2);
        fclose(stand2);

//START STAGE 7 to 8 operations

        fopen_s (&stand2, "stage_8.txt", "a+");
        rewind (stand1);
        fopen_s (&tree2, "treelist_8.txt", "a+");
        rewind (tree1);

        //return stage 8 output//

        fclose(tree1);
        fclose(stand1);

//START STAGE 8 to 9 operations

        fopen_s (&stand1, "stage_9.txt", "a+");
        rewind (stand2);
        fopen_s (&tree1, "treelist_9.txt", "a+");
        rewind (tree2);

        //return stage 9 output//

        fclose(tree2);
        fclose(stand2);

//START STAGE 9 to 10 operations

        fopen_s (&stand2, "stage_99.txt", "a+");
        rewind (stand1);
        rewind (tree1);

        //return stage 10 output//

        fclose(tree1);

//EXPECTED CARBON VALUE @ END OF FINAL STAGE==99

        fopen_s (&C99, "C_99.txt", "w+");
        rewind (stand2);
        fgetpos(stand2, &pos);

        while (!feof (stand2))
        {
                goto label_19;

label_19: fsetpos (stand2, &pos);
```

```
			fscanf_s (stand2, "%i %i %i %i %lf %lf %lf %lf %lf %lf %lf",
				&scan_prev_stg_st, &scan_st, &scan_j, &scan_fire,
				&scan_baa, &scan_bio, &scan_removal, &scan_delta_bio,
				&scan_removal_bio, &scan_mort_bio, &scan_fmort_bio);

			fgetpos (stand2, &pos);

			C = scan_bio * Cf;

			if (feof(stand2))
			{
				fprintf_s (C99, "\n %i %i %i %lf %lf %lf",
					scan_prev_stg_st, scan_st, scan_j, scan_removal,
					scan_removal_bio, C);
				break;
			}

			fscanf_s (stand2, "%i %i %i %i", &scan_prev_stg_st_1, &scan_st_1,
				&scan_j_1, &scan_fire_1);

			if (scan_fire_1 == 0)
			{
				fprintf_s (C99, "\n %i %i %i %lf %lf %lf",
					scan_prev_stg_st, scan_st, scan_j, scan_removal,
					scan_removal_bio, C);

				goto label_19;
			}
			else if (scan_fire_1 == 1)
			{
				fscanf_s (stand2, "%lf %lf %lf %lf %lf %lf %lf",
					&scan_baa_1, &scan_bio_1, &scan_removal_1,
					&scan_delta_bio_1, &scan_removal_bio_1,
					&scan_mort_bio_1, &scan_fmort_bio_1);

				fgetpos (stand2, &pos);

				C_1 = scan_bio_1 * Cf;
				Cp = C * (1 - P_fire) + C_1 * P_fire;

				fprintf_s (C99, "\n %i %i %i %lf %lf %lf",
					scan_prev_stg_st, scan_st, scan_j, scan_removal,
					scan_removal_bio, Cp);

				goto label_19;
			}
		}
		fclose (stand2);

	//START OF MAX CARBON @ START OF STAGE 9

		fopen_s (&C1, "C_9.txt", "w+");
		rewind (C99);

		stage_no = 9;
		Dhorizon = (100 - stage_length * stage_no);
```

```
        fgetpos(C99, &pos);

        while (!feof (C99))
        {
               CCCmax = 0;

               goto label_20;

label_20: fsetpos (C99, &pos);

               fscanf_s (C99, "%i %i %i %lf %lf %lf", &scan_Cprev_stg_st,
                      &scan_Cst, &scan_Cj, &scan_Cremoval, &scan_Cremoval_bio,
                      &scan_Cp);

               fgetpos (C99, &pos);

               CCC = obj_funk(scan_Cremoval_bio, Cf, Dhorizon, Ur, USTd, Pd,
                      scan_Cp);
               CCCmax = max (CCCmax, CCC);

               if (CCC == CCCmax)
               {
                      prev_stg_st = scan_Cprev_stg_st;
                      st = scan_Cst;
                      j = scan_Cj;
                      removal = scan_Cremoval;
                      removal_bio = scan_Cremoval_bio;
               }

               fscanf_s (C99, "%i", &state);

               if (feof(C99))
               {
                      fprintf_s (C1, "\n %i %i %i %lf %lf %lf", prev_stg_st, st,
                             j, removal, removal_bio, CCCmax);
                      break;
               }

               if (state == scan_Cprev_stg_st)
               {
                      goto label_20;
               }
               else fprintf_s (C1, "\n %i %i %i %lf %lf %lf", prev_stg_st, st,
                      j, removal, removal_bio, CCCmax);
        }

//START OF MAX CARBON @ START OF STAGE 8

        fopen_s (&C2, "C_8.txt", "w+");
        rewind (C1);
        rewind (stand1);

        stage_no = 8;

        //return MAX C @ stage 8

        fclose (C1);
        fclose (stand1);
```

```
//START OF MAX CARBON @ START OF STAGE 7

       fopen_s (&C1, "C_7.txt", "w+");
       rewind (C2);
       fopen_s (&stand1, "stage_8.txt", "r+");

       stage_no = 7;

       //return MAX C @ stage 7

       fclose (C2);
       fclose (stand1);

//return MAX C @ stage 6

       fopen_s (&C2, "C_6.txt", "w+");
       rewind (C1);
       fopen_s (&stand1, "stage_7.txt", "r+");

       stage_no = 6;

       //return MAX C @ stage 6

       fclose (C1);
       fclose (stand1);

//return MAX C @ stage 5

       fopen_s (&C1, "C_5.txt", "w+");
       rewind (C2);
       fopen_s (&stand1, "stage_6.txt", "r+");

       stage_no = 5;

       //return MAX C @ stage 5

       fclose (C2);
       fclose (stand1);

//return MAX C @ stage 4

       fopen_s (&C2, "C_4.txt", "w+");
       rewind (C1);
       fopen_s (&stand1, "stage_5.txt", "r+");

       stage_no = 4;

       //return MAX C @ stage 4

       fclose (C1);
       fclose (stand1);

//return MAX C @ stage 3

       fopen_s (&C1, "C_3.txt", "w+");
       rewind (C2);
       fopen_s (&stand1, "stage_4.txt", "r+");
```

```
        stage_no = 3;

        //return MAX C @ stage 3

        fclose (C2);
        fclose (stand1);

//return MAX C @ stage 2

        fopen_s (&C2, "C_2.txt", "w+");
        rewind (C1);
        fopen_s (&stand1, "stage_3.txt", "r+");

        stage_no = 2;

        //return MAX C @ stage 2

        fclose (C1);
        fclose (stand1);

//return MAX C @ stage 1

        fopen_s (&C1, "C_1.txt", "w+");
        rewind (C2);
        fopen_s (&stand1, "stage_2.txt", "r+");

        stage_no = 1;

        //return MAX C @ stage 1

        fclose (C2);
        fclose (stand1);

//return MAX C @ stage 0

        fopen_s (&C2, "C_0.txt", "w+");
        rewind (C1);
        fopen_s (&stand1, "stage_1.txt", "r+");

        stage_no = 0;

        //return MAX C @ stage 0

        fclose (C1);
        fclose (C2);
        fclose (stand1);

//START OF OPTIMAL PATH SEARCH

        fopen_s (&C2, "pathway.txt", "w+");
        fopen_s (&C1, "C_0.txt", "r+");

        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st, &scan_st,
               &scan_j, &scan_removal, &scan_removal_bio, &scan_Cp);
        st = scan_st;
        fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j, scan_removal,
               scan_removal_bio, scan_Cp);
        fclose (C1);
```

```
fopen_s (&C1, "C_1.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;
		fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_2.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;
		fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_3.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;
		fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_4.txt", "r+");

while (!feof (C1))
```

```
{
        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
                &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
                &scan_Cp);

        if (scan_prev_stg_st == st)
        {
                st = scan_st;
                fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
                        scan_removal, scan_removal_bio, scan_Cp);
                fclose (C1);
                break;
        }
}

fopen_s (&C1, "C_5.txt", "r+");

while (!feof (C1))
{
        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
                &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
                &scan_Cp);

        if (scan_prev_stg_st == st)
        {
                st = scan_st;
                fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
                        scan_removal, scan_removal_bio, scan_Cp);
                fclose (C1);
                break;
        }
}

fopen_s (&C1, "C_6.txt", "r+");

while (!feof (C1))
{
        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
                &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
                &scan_Cp);

        if (scan_prev_stg_st == st)
        {
                st = scan_st;
                fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
                        scan_removal, scan_removal_bio, scan_Cp);
                fclose (C1);
                break;
        }
}

fopen_s (&C1, "C_7.txt", "r+");

while (!feof (C1))
{
        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
                &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
                &scan_Cp);
```

```
        if (scan_prev_stg_st == st)
        {
               st = scan_st;
               fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
                      scan_removal, scan_removal_bio, scan_Cp);
               fclose (C1);
               break;
        }
}

fopen_s (&C1, "C_8.txt", "r+");

while (!feof (C1))
{
        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
               &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
               &scan_Cp);

        if (scan_prev_stg_st == st)
        {
               st = scan_st;
               fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
                      scan_removal, scan_removal_bio, scan_Cp);
               fclose (C1);
               break;
        }
}

fopen_s (&C1, "C_9.txt", "r+");

while (!feof (C1))
{
        fscanf_s (C1, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
               &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
               &scan_Cp);

        if (scan_prev_stg_st == st)
        {
               st = scan_st;
               fprintf_s (C2, "\n %i %i %lf %lf %lf", st, scan_j,
                      scan_removal, scan_removal_bio, scan_Cp);
               fclose (C1);
               break;
        }
}

rewind (C99);

while (!feof (C99))
{
        fscanf_s (C99, "%i %i %i %lf %lf %lf", &scan_prev_stg_st,
               &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
               &scan_Cp);

        if (scan_st == st)
        {
               fprintf_s (C2, "\n %lf", scan_Cp);
               fclose (C99);
```

```
                        break;
                }
        }

        fclose (C2);

        return 0;
}

//END OF MAIN PROGRAM
//FUNCTIONS

double fsditrees (double xqmd, int xSDImax)
                {
                        return xSDImax * pow ((xqmd / 10), -1.605);
                }

double frd (double xsdi, int xSDImax)
                {
                        return xsdi / xSDImax;
                }

double fcr (double xht, double xbaa)
                {
                        return (xht - (-1.771 + 0.554 * xht + 0.045 * xbaa)) /
                                xht;
                }

double fcarea (double xdbh, double xtrees)
                {
                        return 3.14159 * ((1.6654 + 0.0355 * xdbh) * (1.6654 +
                                0.0355 * xdbh)) * 0.0023 * xtrees;
                }


double fbatarget (double xbaa, double xredux)
                {
                        return (xbaa * (1 - xredux));
                }

double fcrown (double xheight, double xccfl, double xba, double xdbh)
                {
                        return 1 - (1 / (1 + exp(1.94093 - 0.0065029 * xheight –
                                0.0048737 * xccfl - 0.261573 * log(xba)
                                + 1.08785 * xdbh / xheight)));
                }

double ftrees (double xtrees, double xmort)
                {
                        return xtrees * (1 - xmort);
                }

double frtrees (double xsdi, int xSDImax)
                {
                        return 20 * (1 - (xsdi / xSDImax));
                }

double fba (double xdbh, double xtrees)
```

```
                {
                        return 0.005454 * (xdbh * xdbh) * xtrees;
                }

double fbiomass (double xdbh, double xtrees)
                {
                        return 0.001 * exp(-2.2304 + 2.4435 * log(xdbh * 2.54)) *
                                xtrees;         //Jenkins (2003)
                }

double fqmd (double xbaa, double xtpa)
                {
                        return pow (xbaa /(0.005454 * xtpa), 0.5);
                }

double fsdi (double xqmd, double xtpa)
                {
                        return xtpa * pow ((xqmd / 10), 1.605);
                }

        double fdinc (double xdbh, double xcrown, double xsite, double xbaad,
                double xba)
                {
                        return 2.01 * (exp(- 4.69624 + 0.339513 * log (xdbh + 1) –
                                0.00042826 * (xdbh * xdbh) + 1.19952 * log ((xcrown
                                + 0.2) / 1.2) + 1.15612 * log (xsite - 4.5)
                                - 0.0000446327 * (xbaad * xbaad) / log (xdbh + 5) -
                                0.0237003 * sqrt (xba))) + xdbh;
                }

        double fhinc (double xheight, double xsite)
                {
                        double gea;

                        gea = pow ((log (1 - ((xheight - 4.5) / (xsite - 4.5)) *
                                (1 - exp (-0.00199536 * pow (xsite - 4.5, 0.281176)
                                * pow (50, 1.14354))))) / (-0.00199536 * pow (xsite
                                - 4.5, 0.281176)), 1 / 1.14354);

                        return 1.95 * ((4.5 + (xheight - 4.5) * ((1 - exp (-
                                0.00199536 * pow (xsite - 4.5, 0.281176)
                                * pow (gea + 5, 1.14354))) / (1 - exp (-0.00199536
                                * pow (xsite - 4.5, 0.281176)
                                * pow (gea, 1.14354))))) - xheight) + xheight;
                }

        double fgrowmort (double xdbh, double xcrown, double xsite, double
                xbaad)
                {
                        return (1.9 * (1 / (1 + exp(-(-0.149558 - 0.203923 * xdbh
                                - 7.32001 * xcrown + 0.0133533
                                * xsite + 0.00168508 * xbaad))))) / 100;
                }

//Fire behavior fuel model mortality functions
        double fsh4 (double xht, double xcr)
        {
                if (xht > 100)
```

```
{
	if (xht <= 125)
	{
		if (xcr > 0.8)
		{
			return 0.93;
		}
		else if (0.7 < xcr && xcr <= 0.8)
		{
			return 0.90;
		}
		else if (0.6 < xcr && xcr <= 0.7)
		{
			return 0.84;
		}
		else if (0.5 < xcr && xcr <= 0.6)
		{
			return 0.71;
		}
		else if (0.4 < xcr && xcr <= 0.5)
		{
			return 0.50;
		}
		else if (0.3 < xcr && xcr <= 0.4)
		{
			return 0.34;
		}
		else return 0;
	}
	else if (125 < xht && xht <= 150)
	{
		if (xcr > 0.8)
		{
			return 0.72;
		}
		else if (0.7 < xcr && xcr <= 0.8)
		{
			return 0.60;
		}
		else if (0.6 < xcr && xcr <= 0.7)
		{
			return 0.45;
		}
		else if (0.5 < xcr && xcr <= 0.6)
		{
			return 0.35;
		}
		else if (0.4 < xcr && xcr <= 0.5)
		{
			return 0.29;
		}
		else return 0;
	}
	else if (150 < xht && xht <= 175)
	{
		if (xcr > 0.8)
		{
			return 0.50;
```

```
                    }
                    else if (0.7 < xcr && xcr <= 0.8)
                    {
                          return 0.40;
                    }
                    else if (0.6 < xcr && xcr <= 0.7)
                    {
                          return 0.34;
                    }
                    else if (0.5 < xcr && xcr <= 0.6)
                    {
                          return 0.28;
                    }
                    else return 0;
             }
             else
             {
                    if (xcr > 0.8)
                    {
                          return 0.39;
                    }
                    else if (0.7 < xcr && xcr <= 0.8)
                    {
                          return 0.34;
                    }
                    else if (0.6 < xcr && xcr <= 0.7)
                    {
                          return 0.31;
                    }
                    else return 0;
             }
      }      //End of "if ht > 100"
      else return 0.98;
}

double fsh5 (double xht, double xcr)
{
      if (xht > 0 && xcr > 0)
      {
             return 0.98;
      }
}

double fsh6 (double xht, double xcr)
{
      if (xht > 150)
      {
             if (xht <= 175)
             {
                    if (xcr > 0.8)
                    {
                          return 0.95;
                    }
                    else if (0.7 < xcr && xcr <= 0.8)
                    {
                          return 0.93;
                    }
                    else if (0.6 < xcr && xcr <= 0.7)
```

```
                {
                        return 0.90;
                }
                else if (0.5 < xcr && xcr <= 0.6)
                {
                        return 0.83;
                }
                else if (0.4 < xcr && xcr <= 0.5)
                {
                        return 0.67;
                }
                else if (0.3 < xcr && xcr <= 0.4)
                {
                        return 0.41;
                }
                else return 0.24;
        }
        else
        {
                if (xcr > 0.8)
                {
                        return 0.85;
                }
                else if (0.7 < xcr && xcr <= 0.8)
                {
                        return 0.77;
                }
                else if (0.6 < xcr && xcr <= 0.7)
                {
                        return 0.64;
                }
                else if (0.5 < xcr && xcr <= 0.6)
                {
                        return 0.47;
                }
                else if (0.4 < xcr && xcr <= 0.5)
                {
                        return 0.34;
                }
                else if (0.3 < xcr && xcr <= 0.4)
                {
                        return 0.19;
                }
                else return 0;
        }
}       //End of "if ht > 150"
else return 0.98;
}

double fsb1 (double xht, double xcr)
{
        if (xht <= 100)
        {
                if (xht > 75)
                {
                        if (xcr > 0.8)
                        {
                                return 0.17;
```

```
                }
                else return 0;
            }
            else if (xht > 50)
            {
                if (xcr > 0.8)
                {
                    return 0.29;
                }
                else return 0;
            }
            else
            {
                if (xcr > 0.8)
                {
                    return 0.35;
                }
                else if (0.7 < xcr && xcr <= 0.8)
                {
                    return 0.32;
                }
                else if (0.6 < xcr && xcr <= 0.7)
                {
                    return 0.24;
                }
                else return 0;
            }
        }       //End of "if ht <= 100"
        else return 0;
}

double fsb2 (double xht, double xcr)
{
        if (xht > 75)
        {
            if (xht <= 100)
            {
                if (xcr > 0.8)
                {
                    return 0.91;
                }
                else if (0.7 < xcr && xcr <= 0.8)
                {
                    return 0.86;
                }
                else if (0.6 < xcr && xcr <= 0.7)
                {
                    return 0.78;
                }
                else if (0.5 < xcr && xcr <= 0.6)
                {
                    return 0.62;
                }
                else if (0.4 < xcr && xcr <= 0.5)
                {
                    return 0.42;
                }
                else if (0.3 < xcr && xcr <= 0.4)
```

```
        {
                return 0.32;
        }
        else return 0;
}
else if (100 < xht && xht <= 125)
{
        if (xcr > 0.8)
        {
                return 0.61;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.48;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.38;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
                return 0.33;
        }
        else if (0.4 < xcr && xcr <= 0.5)
        {
                return 0.14;
        }
        else return 0;
}
else if (125 < xht && xht <= 150)
{
        if (xcr > 0.8)
        {
                return 0.41;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.35;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.32;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
                return 0.13;
        }
        else return 0;
}
else if (150 < xht && xht <= 175)
{
        if (xcr > 0.8)
        {
                return 0.35;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.32;
```

```
				}
				else if (0.6 < xcr && xcr <= 0.7)
				{
					return 0.21;
				}
				else return 0;
			}
			else
			{
				if (xcr > 0.8)
				{
					return 0.33;
				}
				else if (0.7 < xcr && xcr <= 0.8)
				{
					return 0.28;
				}
				else return 0;
			}
		}	//End of "if ht > 75"
		else return 0.98;
	}

	double ftl3 (double xht, double xcr)
	{
		if (xht > 0 && xcr > 0)
		{
			return 0;
		}
	}

	double ftu1 (double xht, double xcr)
	{
		if (xht > 0 && xcr > 0)
		{
			return 0;
		}
	}

	double ftu5 (double xht, double xcr)
	{
		if (xht > 100)
		{
			if (xht <= 125)
			{
				if (xcr > 0.8)
				{
					return 0.95;
				}
				else if (0.7 < xcr && xcr <= 0.8)
				{
					return 0.93;
				}
				else if (0.6 < xcr && xcr <= 0.7)
				{
					return 0.89;
				}
				else if (0.5 < xcr && xcr <= 0.6)
```

```
        {
                return 0.82;
        }
        else if (0.4 < xcr && xcr <= 0.5)
        {
                return 0.64;
        }
        else if (0.3 < xcr && xcr <= 0.4)
        {
                return 0.39;
        }
        else return 0.20;
}
else if (125 < xht && xht <= 150)
{
        if (xcr > 0.8)
        {
                return 0.78;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.67;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.52;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
                return 0.38;
        }
        else if (0.4 < xcr && xcr <= 0.5)
        {
                return 0.32;
        }
        else return 0;
}
else if (150 < xht && xht <= 175)
{
        if (xcr > 0.8)
        {
                return 0.55;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.43;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.35;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
                return 0.31;
        }
        else return 0;
}
else
```

```
                {
                        if (xcr > 0.8)
                        {
                                return 0.41;
                        }
                        else if (0.7 < xcr && xcr <= 0.8)
                        {
                                return 0.35;
                        }
                        else if (0.6 < xcr && xcr <= 0.7)
                        {
                                return 0.32;
                        }
                        else if (0.5 < xcr && xcr <= 0.6)
                        {
                                return 0.14;
                        }
                        else return 0;
                }
        }       //End of "if ht > 100"
        else return 0.98;
}

double fire_prob (double xmFRI, int xstage_length)
        {
                return (exp (-(1 / xmFRI) * xstage_length)) * ((1 / xmFRI)
                        * xstage_length);
        }

double obj_funk (double xbio, double xCf, int xDhorizon, double xUr, double
        xUSTd, double xPd, double xCp)
        {
                return (xbio * xCf * ((xUr * xUSTd) * (1 - xPd *
                        xDhorizon) + xUr * (1 - xUSTd))) + xCp;
        }
```

APPENDIX 2

CFIRE SPRS – Fire suppression source code

```
#include <iostream>
#include <fstream>
#include <cmath>
#include <vector>

using namespace std;

double fbatarget (double xbaa, double xredux);

double fcr (double xht, double xbaa);
double fcarea (double xdbh, double xtrees);
double fcrown (double xheight, double xccfl, double xba, double xdbh);
double ftrees (double xtrees, double xmort);
double fgrowmort (double xdbh, double xcrown, double xsite, double
       xbaad);
double fdinc (double xdbh, double xcrown, double xsite, double xbaad,
       double xba);
double fhinc (double xheight, double xsite);
double fba (double xdbh, double xtrees);
double fbiomass (double xdbh, double xtrees);

double frtrees (double xsdi, int xSDImax);

double fqmd (double xbaa, double xtpa);
double fsdi (double xqmd, double xtpa);
double frd (double xsdi, int xSDImax);
double fsditrees (double xqmd, int xSDImax);

double ftl3 (double xht, double xcr);
double ftu1 (double xht, double xcr);
double ftu5 (double xht, double xcr);
double fsb1 (double xht, double xcr);
double fsb2 (double xht, double xcr);
double fsh4 (double xht, double xcr);
double fsh5 (double xht, double xcr);
double fsh6 (double xht, double xcr);

double ftl3area(double xroad_loc, double xstand_dtr);
double ftu1area(double xroad_loc, double xstand_dtr);
double ftu5area(double xroad_loc, double xstand_dtr);
double fsb1area(double xroad_loc, double xstand_dtr);
double fsb2area(double xroad_loc, double xstand_dtr);
double fsh4area(double xroad_loc, double xstand_dtr);
double fsh5area(double xroad_loc, double xstand_dtr);
double fsh6area(double xroad_loc, double xstand_dtr);
```

```
double ftl3cost(double xroad_loc, double xstand_dtr);
double ftu1cost(double xroad_loc, double xstand_dtr);
double ftu5cost(double xroad_loc, double xstand_dtr);
double fsb1cost(double xroad_loc, double xstand_dtr);
double fsb2cost(double xroad_loc, double xstand_dtr);
double fsh4cost(double xroad_loc, double xstand_dtr);
double fsh5cost(double xroad_loc, double xstand_dtr);
double fsh6cost(double xroad_loc, double xstand_dtr);

double obj_funk (double xbio, double xCf, int xDhorizon, double xUr, double
       xnUr, double xUSTd, double xPd, double xCWDd, double xCp);

double fire_prob (double xmFRI, int xstage_length);

int main ()
{
       int treat_no = 6; //DEFINE NUMBER OF TREATMENTS (j)
       double redux_incr = 0.15;   //TREATMENT BA REDUCTION INCREMENT
       double site = 80;    //SITE INDEX
       double mFRI = 8;     //(MWDF: 400, DMDF: 80, MCME: 8)
       double road_loc = 1; //Road location: below stand = 0, above stand = 1
       double stand_dtr = 4;       //Stand distance-to-road: 0% = 0, 25% = 1,
                                   //50% = 2, 75% = 3, 100% = 4 | if road_loc
                                   == 0, dtr <> 4 | if road_loc == 1, dtr <> 0

       double Ur = 0.80;
       double USTd = 0.75;
       double Pd = 0.01;
       double CWDd = 0.029;

       double Cf = 0.50;
       double nUr = 1 - Ur;
       int Dhorizon;
       int stage_length = 10;
       int stage_no;
       int stand_area = 256;       //Stand area = 256 acres (5280' x (5280' /
                                   //2.5)) | slope distance, slope distance /
                                   length-to-width ratio of fire ellipse

       int decay_horizon = 10;
       double decay_mort = 0.029;
       double release_fmort = 0.048;

       int SDImax = 525;
       const signed int endofrecord = -1;
       int eomegarec;

       double redux;

       int scan_prev_stg_st;
       int st, scan_st;
       int scan_j;
       int fire, scan_fire;
       double baa, scan_baa;
       double bio, scan_bio;
       double sdi, scan_sdi;
       double ccf, scan_ccf;
       double removal, scan_removal;
```

```
double delta_bio, scan_delta_bio;
double removal_bio, scan_removal_bio;
double mort_bio, scan_mort_bio;
double fmort_bio, scan_fmort_bio;
double fmort_area, scan_fmort_area;
double sprs_cost, scan_sprs_cost;
double qmd;
double ht;
double cr;
double tpa;
double rd;
double sdi_tpa;
double sdi_qmd;

int species;
double dbh, scan_dbh;
double trees, trees1, scan_trees;
double height, scan_height;
double ba, ba1, scan_ba;

double baad;
double biomass, biomass1;
double crown;
double pmort;
double fmort;
double removal_biomass;
double mort_trees, mort_biomass;
double fmort_trees, fmort_biomass;
double basum;
double htsum;
double baatarg;
double carea, sccarea, carea1;
double ccfl;
double batarg;
double treestarg;
double sdi_treestarg;

int rspecies = 202;
double rdbh = 2;
double rtrees;
double rheight = 15;
double rba;

int prev_stg_st, scan_prev_stg_st_1, scan_prev_stg_st_2,
       scan_Cprev_stg_st, scan_Cprev_stg_st_1;
int state, scan_st_1, scan_Cst, scan_Cst_1;
int j, scan_j_1, scan_Cj, scan_Cj_1;
int scan_fire_1;
double scan_baa_1;
double scan_bio_1;
double scan_sdi_1;
double scan_ccf_1;
double scan_removal_1, scan_Cremoval, scan_Cremoval_1;
double scan_delta_bio_1;
double scan_removal_bio_1, scan_Cremoval_bio, scan_Cremoval_bio_1;
double scan_mort_bio_1;
double scan_fmort_bio_1;
double scan_fmort_area_1, scan_Cfmort_area, scan_Cfmort_area_1;
```

```
	double scan_sprs_cost_1, scan_Csprs_cost, scan_Csprs_cost_1;

	double C, C_1, Cp, scan_Cp, scan_Cp_1, CCC, CCCmax;

	double P_fire;

	P_fire = fire_prob(mFRI, stage_length);

	FILE *stand1;
	FILE *stand2;
	FILE *tree1;
	FILE *tree2;
	fpos_t pos;
	fpos_t pos1;
	FILE *C1;
	FILE *C2;
	FILE *C99;

	fopen_s (&stand2, "stage_0.txt", "a+");

	fopen_s (&stand1, "stand_xx.txt", "r+");

	fscanf_s (stand1, "%lf %lf %lf %lf", &qmd, &ht, &scan_baa, &tpa);
	fclose(stand1);

	st = 0;
	ccf = 0;
	bio = 0;

	cr = fcr(ht, scan_baa);
	sdi = fsdi(qmd, tpa);

	fopen_s (&tree2, "treelist_0.txt", "a+");

	fopen_s (&tree1, "tree_xx.txt", "r+");

	while (!feof (tree1))
	{
		fscanf_s (tree1, "%i %lf %lf %lf %lf", &species, &scan_dbh,
			&scan_trees, &scan_height, &scan_ba);

		fprintf_s (tree2, "\n %i %i %lf %lf %lf %lf", st, species,
			scan_dbh, scan_trees, scan_height, scan_ba);

		carea = fcarea(scan_dbh, scan_trees);
		ccf = ccf + carea;
		biomass = fbiomass(scan_dbh, scan_trees);
		bio = bio + biomass;
	}
	fclose(tree1);

	fprintf_s (stand2, "\n %i %lf %lf %lf %lf", st, scan_baa, bio, sdi,
		ccf);

//STAGE 0 to 1 operations

	fopen_s (&stand1, "stage_1.txt", "a+");
	rewind (stand2);
```

```
	fopen_s (&tree1, "treelist_1.txt", "a+");
	rewind (tree2);

	fscanf_s (stand2, "%i %lf %lf %lf %lf", &scan_prev_stg_st, &scan_baa,
		&scan_bio, &scan_sdi, &scan_ccf);

	fclose(stand2);

	sdi_tpa = 0;
	redux = 0;
	st = 0;

	vector< vector<double> > treev;
	while (!feof (tree2))
	{
		fscanf_s (tree2, "%i %i %lf %lf %lf %lf", &scan_prev_stg_st,
			&species, &scan_dbh, &scan_trees, &scan_height, &scan_ba);

		sdi_tpa = sdi_tpa + scan_trees;

		vector<double> row(5);
		row[0] = species;
		row[1] = scan_dbh;
		row[2] = scan_trees;
		row[3] = scan_height;
		row[4] = scan_ba;

		treev.push_back(row);
	}

	fclose(tree2);

	for (int j = 0; j < treat_no; j++)
	{
		fire = 0;
		baatarg = fbatarget(scan_baa, redux);
		removal = scan_baa - baatarg;

		bio = 0;
		removal_bio = 0;
		mort_bio = 0;
		fmort_bio = 0;
		fmort_area = 0;
		sprs_cost = 0;
		basum = 0;
		baa = 0;
		tpa = 0;
		htsum = 0;
		baad = scan_baa;
		ccf = 0;
		ccfl = scan_ccf;

		int i = 0;

//REGENERATION
		rtrees = frtrees(scan_sdi, SDImax);
```

```
                if (rtrees > 0)
                {
                        rba = fba(rdbh, rtrees);

                        fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
                                rspecies, rdbh, rtrees, rheight, rba);

                        biomass = fbiomass(rdbh, rtrees);
                        bio = bio + biomass;
                        htsum = htsum + rheight;
                        tpa = tpa + rtrees;
                        baa = baa + rba;
                        carea = fcarea(rdbh, rtrees);
                        ccf = ccf + carea;
                }
//END Regeneration

                for (int k = 0; k < static_cast <double> (treev.size()); k++)
                {
                        baad = baad - treev[k][4];
                        sccarea = fcarea(treev[k][1], treev[k][2]);
                        ccfl = ccfl - sccarea;

                        basum = treev[k][4] + basum;

                        if (removal == 0)
                        {
                                i = i + 1;

                                species = static_cast <int> (treev[k][0]);
                                crown = fcrown(treev[k][3], ccfl, treev[k][4],
                                        treev[k][1]);
                                pmort = fgrowmort(treev[k][1], crown, site, baad);

                                if (scan_sdi > SDImax)
                                {
                                        sdi_qmd = fqmd(scan_baa, sdi_tpa);
                                        sdi_treestarg = fsditrees(sdi_qmd, SDImax);

                                        pmort = pmort + ((sdi_tpa - sdi_treestarg) /
                                                sdi_tpa);
                                }
                                else pmort = pmort;

                                if (pmort < 1)
                                {
                                        pmort = pmort;
                                }
                                else pmort = 0.95;

                                trees = ftrees(treev[k][2], pmort);
                                dbh = fdinc(treev[k][1], crown, site, baad,
                                        treev[k][4]);
                                height = fhinc(treev[k][3], site);
                                ba = fba(dbh, trees);
                                biomass = fbiomass(dbh, trees);
                                mort_trees = treev[k][2] - trees;
                                mort_biomass = fbiomass(treev[k][1], mort_trees);
```

```
		carea = fcarea(dbh, trees);

		fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
			species, dbh, trees, height, ba);

		bio = bio + biomass;
		htsum = htsum + height;
		tpa = tpa + trees;
		baa = baa + ba;
		ccf = ccf + carea;
		mort_bio = mort_bio + mort_biomass;
	}
	if (basum <= removal)
	{
		removal_biomass = fbiomass(treev[k][1],
			treev[k][2]);
		removal_bio = removal_bio + removal_biomass;
	}
	if (basum > removal && removal > 0 && i == 0)
	{
		batarg = basum - removal;
		treestarg = (batarg / treev[k][4]) * treev[k][2];

		i = i + 1;

		species = static_cast <int> (treev[k][0]);
		crown = fcrown(treev[k][3], ccfl, treev[k][4] –
			batarg, treev[k][1]);
		pmort = fgrowmort(treev[k][1], crown, site, baad);

		if (pmort < 1)
		{
			pmort = pmort;
		}
		else pmort = 0.95;

		trees = ftrees(treestarg, pmort);
		dbh = fdinc(treev[k][1], crown, site, baad,
			treev[k][4] - batarg);
		height = fhinc(treev[k][3], site);
		ba = fba(dbh, trees);
		biomass = fbiomass(dbh, trees);
		removal_biomass = fbiomass(treev[k][1], treev[k][2]
			- treestarg);
		mort_trees = treestarg - trees;
		mort_biomass = fbiomass(treev[k][1], mort_trees);
		carea = fcarea(dbh, trees);

		fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
			species, dbh, trees, height, ba);

		bio = bio + biomass;
		htsum = htsum + height;
		tpa = tpa + trees;
		baa = baa + ba;
		ccf = ccf + carea;
		removal_bio = removal_bio + removal_biomass;
		mort_bio = mort_bio + mort_biomass;
```

```
        }
        else if (basum > removal && removal > 0)
        {
                i = i + 1;

                species = static_cast <int> (treev[k][0]);
                crown = fcrown(treev[k][3], ccfl, treev[k][4],
                        treev[k][1]);
                pmort = fgrowmort(treev[k][1], crown, site, baad);

                if (pmort < 1)
                {
                        pmort = pmort;
                }
                else pmort = 0.95;

                trees = ftrees(treev[k][2], pmort);
                dbh = fdinc(treev[k][1], crown, site, baad,
                        treev[k][4]);
                height = fhinc(treev[k][3], site);
                ba = fba(dbh, trees);
                biomass = fbiomass(dbh, trees);
                mort_trees = treev[k][2] - trees;
                mort_biomass = fbiomass(treev[k][1], mort_trees);
                carea = fcarea(dbh, trees);

                fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
                        species, dbh, trees, height, ba);

                bio = bio + biomass;
                htsum = htsum + height;
                tpa = tpa + trees;
                baa = baa + ba;
                ccf = ccf + carea;
                mort_bio = mort_bio + mort_biomass;
        }
}

if (rtrees > 0)
{
        i = i + 1;
}

ht = htsum / i;
cr = fcr(ht, baa);
qmd = fqmd(baa, tpa);
sdi = fsdi(qmd, tpa);
delta_bio = bio - scan_bio;
mort_bio = mort_bio * (1 - decay_mort * decay_horizon);
bio = bio + mort_bio;

fprintf_s (tree1, "\n %i", endofrecord);
fprintf_s (stand1, "\n %i %i %i %i %lf %lf %lf %lf %lf %lf %lf
        %lf %lf %lf %lf", scan_prev_stg_st, st, j, fire, baa, bio,
        sdi, ccf, removal, delta_bio, removal_bio, mort_bio,
        fmort_bio, fmort_area, sprs_cost);

st = st + 1;
```

```
fire = 1;
rd = frd(sdi, SDImax);

if (j == 0)
{
	if (rd >= 0.4)
	{
		if (qmd > 5)
		{
			fmort = ftl3(ht, cr);
			fmort_area = ftl3area(road_loc, stand_dtr);
			sprs_cost = ftl3cost(road_loc, stand_dtr);
		}
		else
		{
			fmort = fsh4(ht, cr);
			fmort_area = fsh4area(road_loc, stand_dtr);
			sprs_cost = fsh4cost(road_loc, stand_dtr);
		}
	}
	else
	{
		if (qmd > 9)
		{
			fmort = fsb1(ht, cr);
			fmort_area = fsb1area(road_loc, stand_dtr);
			sprs_cost = fsb1cost(road_loc, stand_dtr);
		}
		else if (qmd <= 5)
		{
			fmort = ftu5(ht, cr);
			fmort_area = ftu5area(road_loc, stand_dtr);
			sprs_cost = ftu5cost(road_loc, stand_dtr);
		}
		else
		{
			fmort = fsh4(ht, cr);
			fmort_area = fsh4area(road_loc, stand_dtr);
			sprs_cost = fsh4cost(road_loc, stand_dtr);
		}
	}
}
else
{
	if (rd >= 0.4)
	{
		if (qmd > 5)
		{
			fmort = ftu1(ht, cr);
			fmort_area = ftu1area(road_loc, stand_dtr);
			sprs_cost = ftu1cost(road_loc, stand_dtr);
		}
		else
		{
			fmort = fsh6(ht, cr);
			fmort_area = fsh6area(road_loc, stand_dtr);
			sprs_cost = fsh6cost(road_loc, stand_dtr);
		}
```

```
                }
                else
                {
                        if (qmd > 9)
                        {
                                fmort = fsb2(ht, cr);
                                fmort_area = fsb2area(road_loc, stand_dtr);
                                sprs_cost = fsb2cost(road_loc, stand_dtr);
                        }
                        else if (qmd <= 5)
                        {
                                fmort = fsh5(ht, cr);       //NEW
                                fmort_area = fsh5area(road_loc, stand_dtr);
                                sprs_cost = fsh5cost(road_loc, stand_dtr);
                        }
                        else
                        {
                                fmort = fsh6(ht, cr);
                                fmort_area = fsh6area(road_loc, stand_dtr);
                                sprs_cost = fsh6cost(road_loc, stand_dtr);
                        }
                }
        }

        if (fmort > 0)
        {
                bio = 0;
                removal_bio = 0;
                mort_bio = 0;
                fmort_bio = 0;
                basum = 0;
                baa = 0;
                tpa = 0;
                baad = scan_baa;
                ccf = 0;
                ccfl = scan_ccf;

                i = 0;

//REGENERATION
                rtrees = frtrees(scan_sdi, SDImax) * (1 - fmort);

                if (rtrees > 0)
                {
                        rba = fba(rdbh, rtrees);

                        fprintf_s (tree1, "\n %i %i %lf %lf %lf %lf", st,
                                rspecies, rdbh, rtrees, rheight, rba);

                        biomass = fbiomass(rdbh, rtrees);
                        bio = bio + biomass;
                        tpa = tpa + rtrees;
                        baa = baa + rba;
                        carea = fcarea(rdbh, rtrees);
                        ccf = ccf + carea;
                }
//END Regeneration
```

```
for (int m = 0; m < static_cast <double> (treev.size());
       m++)
{
       baad = baad - treev[m][4];
       sccarea = fcarea(treev[m][1], treev[m][2]);
       ccfl = ccfl - sccarea;

       basum = treev[m][4] + basum;

       if (removal == 0)
       {
              i = i + 1;

              species = static_cast <int> (treev[m][0]);
              crown = fcrown(treev[m][3], ccfl,
                     treev[m][4], treev[m][1]);
              pmort = fgrowmort(treev[m][1], crown, site,
                     baad);

              if (scan_sdi > SDImax)
              {
                     sdi_qmd = fqmd(scan_baa, sdi_tpa);
                     sdi_treestarg = fsditrees(sdi_qmd,
                            SDImax);

                     pmort = pmort + ((sdi_tpa –
                            sdi_treestarg) / sdi_tpa);
              }
              else
              {
                     pmort = pmort;
              }

              if (pmort < 1)
              {
                     pmort = pmort;
              }
              else pmort = 0.95;

              trees1 = ftrees(treev[m][2], pmort) *
                     ((stand_area - fmort_area) /
                     stand_area);
              trees = ftrees(treev[m][2], fmort) *
                     (fmort_area / stand_area);
              dbh = fdinc(treev[m][1], crown, site, baad,
                     treev[m][4]);
              height = fhinc(treev[m][3], site);
              ba1 = fba(dbh, trees1);
              ba = fba(dbh, trees);
              biomass1 = fbiomass(dbh, trees1);
              biomass = fbiomass(dbh, trees);
              fmort_trees = treev[m][2] * (fmort_area /
                     stand_area) - trees;
              fmort_biomass = fbiomass(treev[m][1],
                     fmort_trees);
              mort_trees = treev[m][2] * ((stand_area –
                     fmort_area) / stand_area) - trees1;
              mort_biomass = fbiomass(treev[m][1],
```

```
                mort_trees);
        carea1 = fcarea(dbh, trees1);
        carea = fcarea(dbh, trees);

        fprintf_s (tree1, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees1,
                height, ba1);
        fprintf_s (tree1, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees,
                height, ba);

        bio = bio + biomass1 + biomass;
        htsum = htsum + height;
        tpa = tpa + trees1 + trees;
        baa = baa + ba1 + ba;
        ccf = ccf + carea1 + carea;
        mort_bio = mort_bio + mort_biomass;
        fmort_bio = fmort_bio + fmort_biomass;
}
if (basum <= removal)
{
        removal_biomass = fbiomass(treev[m][1],
                treev[m][2]);
        removal_bio = removal_bio + removal_biomass;
}
if (basum > removal && removal > 0 && i == 0)
{
        batarg = basum - removal;
        treestarg = (batarg / treev[m][4]) *
                treev[m][2];

        i = i + 1;

        species = static_cast <int> (treev[m][0]);
        crown = fcrown(treev[m][3], ccfl,
                treev[m][4] - batarg, treev[m][1]);
        pmort = fgrowmort(treev[m][1], crown, site,
                baad);

        if (pmort < 1)
        {
                pmort = pmort;
        }
        else pmort = 0.95;

        trees1 = ftrees(treestarg, pmort) *
                ((stand_area - fmort_area) /
                stand_area);
        trees = ftrees(treestarg, fmort) *
                (fmort_area / stand_area);
        dbh = fdinc(treev[m][1], crown, site, baad,
                treev[m][4] - batarg);
        height = fhinc(treev[m][3], site);
        ba1 = fba(dbh, trees1);
        ba = fba(dbh, trees);
        biomass1 = fbiomass(dbh, trees1);
        biomass = fbiomass(dbh, trees);
        removal_biomass = fbiomass(treev[m][1],
```

```
                treev[m][2] - treestarg);
        fmort_trees = treestarg * (fmort_area /
                stand_area) - trees;
        fmort_biomass = fbiomass(treev[m][1],
                fmort_trees);
        mort_trees = treestarg * ((stand_area –
                fmort_area) / stand_area) - trees1;
        mort_biomass = fbiomass(treev[m][1],
                mort_trees);
        carea1 = fcarea(dbh, trees1);
        carea = fcarea(dbh, trees);

        fprintf_s (tree1, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees1,
                height, ba1);
        fprintf_s (tree1, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees,
                height, ba);

        bio = bio + biomass1 + biomass;
        htsum = htsum + height;
        tpa = tpa + trees1 + trees;
        baa = baa + ba1 + ba;
        ccf = ccf + carea1 + carea;
        removal_bio = removal_bio + removal_biomass;
        mort_bio = mort_bio + mort_biomass;
        fmort_bio = fmort_bio + fmort_biomass;
}
else if (basum > removal && removal > 0)
{
        i = i + 1;

        species = static_cast <int> (treev[m][0]);
        crown = fcrown(treev[m][3], ccfl,
                treev[m][4], treev[m][1]);
        pmort = fgrowmort(treev[m][1], crown, site,
                baad);

        if (pmort < 1)
        {
                pmort = pmort;
        }
        else pmort = 0.95;

        trees1 = ftrees(treev[m][2], pmort) *
                ((stand_area - fmort_area) /
                stand_area);
        trees = ftrees(treev[m][2], fmort) *
                (fmort_area / stand_area);
        dbh = fdinc(treev[m][1], crown, site, baad,
                treev[m][4]);
        height = fhinc(treev[m][3], site);
        ba1 = fba(dbh, trees1);
        ba = fba(dbh, trees);
        biomass1 = fbiomass(dbh, trees1);
        biomass = fbiomass(dbh, trees);
        fmort_trees = treev[m][2] * (fmort_area /
                stand_area) - trees;
```

```
                                fmort_biomass = fbiomass(treev[m][1],
                                       fmort_trees);

                                mort_trees = treev[m][2] * ((stand_area –
                                       fmort_area) / stand_area) - trees1;
                                mort_biomass = fbiomass(treev[m][1],
                                       mort_trees);
                                carea1 = fcarea(dbh, trees1);
                                carea = fcarea(dbh, trees);

                                fprintf_s (tree1, "\n %i %i %lf %lf %lf
                                       %lf", st, species, dbh, trees1,
                                       height, ba1);
                                fprintf_s (tree1, "\n %i %i %lf %lf %lf
                                       %lf", st, species, dbh, trees,
                                       height, ba);

                                bio = bio + biomass1 + biomass;
                                htsum = htsum + height;
                                tpa = tpa + trees1 + trees;
                                baa = baa + ba1 + ba;
                                ccf = ccf + carea1 + carea;
                                mort_bio = mort_bio + mort_biomass;
                                fmort_bio = fmort_bio + fmort_biomass;
                         }
                  }
                  qmd = fqmd(baa, tpa);
                  sdi = fsdi(qmd, tpa);
                  mort_bio = mort_bio * (1 - decay_mort * decay_horizon);
                  fmort_bio = fmort_bio * (1 - release_fmort);
                  bio = bio + mort_bio + fmort_bio;
                  delta_bio = bio - scan_bio;

                  fprintf_s (tree1, "\n %i", endofrecord);
                  fprintf_s (stand1, "\n %i %i %i %i %lf %lf %lf %lf %lf %lf
                         %lf %lf %lf %lf %lf", scan_prev_stg_st, st, j,
                         fire, baa, bio, sdi, ccf, removal, delta_bio,
                         removal_bio, mort_bio, fmort_bio, fmort_area,
                         sprs_cost);

                  st = st + 1;
           }

           redux = redux + redux_incr;

           if (scan_sdi <= SDImax * 0.1)
           {
                  break;
           }
    }

//STAGE 1 to 2 operations

    fopen_s (&stand2, "stage_2.txt", "a+");
    rewind (tree1);
    fopen_s (&tree2, "treelist_2.txt", "a+");
    rewind (stand1);
```

```
st = 0;

while (!feof (stand1))
{
	fscanf_s (stand1, "%i %i %i %i %lf %lf %lf %lf %lf %lf %lf %lf
		%lf %lf %lf", &scan_prev_stg_st, &scan_st, &scan_j,
		&scan_fire, &scan_baa, &scan_bio, &scan_sdi, &scan_ccf,
		&scan_removal, &scan_delta_bio, &scan_removal_bio,
		&scan_mort_bio, &scan_fmort_bio,
		&scan_fmort_area, &scan_sprs_cost);

	sdi_tpa = 0;
	redux = 0;

	vector< vector<double> > treev;

	fgetpos (tree1, &pos);

	goto label_1;

label_1: fsetpos (tree1, &pos);

	fscanf_s (tree1, "%i", &eomegarec);

	if (eomegarec >= 0)
	{
		fscanf_s (tree1, "%i %lf %lf %lf %lf", &species,
			&scan_dbh, &scan_trees, &scan_height, &scan_ba);

		sdi_tpa = sdi_tpa + scan_trees;

		vector<double> row(5);
		row[0] = species;
		row[1] = scan_dbh;
		row[2] = scan_trees;
		row[3] = scan_height;
		row[4] = scan_ba;

		treev.push_back(row);

		fscanf_s (tree1, "\n");
		fgetpos (tree1, &pos);
		goto label_1;
	}
	else
	{
		fscanf_s (tree1, "\n");
		fgetpos (tree1, &pos);
		goto label_2;
	}

label_2: for (int j = 0; j < treat_no; j++)
	{

		fire = 0;
		baatarg = fbatarget(scan_baa, redux);
		removal = scan_baa - baatarg;
```

```
                    bio = 0;
                    removal_bio = 0;
                    mort_bio = 0;
                    fmort_bio = 0;
                    fmort_area = 0;
                    sprs_cost = 0;
                    basum = 0;
                    baa = 0;
                    tpa = 0;
                    htsum = 0;
                    baad = scan_baa;
                    ccf = 0;
                    ccfl = scan_ccf;

                    int i = 0;

//REGENERATION
                    rtrees = frtrees(scan_sdi, SDImax);

                    if (rtrees > 0)
                    {
                           rba = fba(rdbh, rtrees);

                           fprintf_s (tree2, "\n %i %i %lf %lf %lf %lf", st,
                                  rspecies, rdbh, rtrees, rheight, rba);

                           biomass = fbiomass(rdbh, rtrees);
                           bio = bio + biomass;
                           htsum = htsum + rheight;
                           tpa = tpa + rtrees;
                           baa = baa + rba;
                           carea = fcarea(rdbh, rtrees);
                           ccf = ccf + carea;
                    }
//END Regeneration

                    for (int k = 0; k < static_cast <double> (treev.size());
                           k++)
                    {
                           baad = baad - treev[k][4];
                           sccarea = fcarea(treev[k][1], treev[k][2]);
                           ccfl = ccfl - sccarea;

                           basum = treev[k][4] + basum;

                           if (removal == 0)
                           {
                                  i = i + 1;

                                  species = static_cast <int> (treev[k][0]);
                                  crown = fcrown(treev[k][3], ccfl,
                                         treev[k][4], treev[k][1]);
                                  pmort = fgrowmort(treev[k][1], crown, site,
                                         baad);

                                  if (scan_sdi > SDImax)
                                  {
                                         sdi_qmd = fqmd(scan_baa, sdi_tpa);
```

```
                sdi_treestarg = fsditrees(sdi_qmd,
                        SDImax);

                pmort = pmort + ((sdi_tpa –
                        sdi_treestarg) / sdi_tpa);
        }
        else pmort = pmort;

        if (pmort < 1)
        {
                pmort = pmort;
        }
        else pmort = 0.95;

        trees = ftrees(treev[k][2], pmort);
        dbh = fdinc(treev[k][1], crown, site, baad,
                treev[k][4]);
        height = fhinc(treev[k][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        mort_trees = treev[k][2] - trees;
        mort_biomass = fbiomass(treev[k][1],
                mort_trees);
        carea = fcarea(dbh, trees);

        fprintf_s (tree2, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees,
                height, ba);

        bio = bio + biomass;
        htsum = htsum + height;
        tpa = tpa + trees;
        baa = baa + ba;
        ccf = ccf + carea;
        mort_bio = mort_bio + mort_biomass;
}
if (basum <= removal)
{
        removal_biomass = fbiomass(treev[k][1],
                treev[k][2]);
        removal_bio = removal_bio + removal_biomass;
}
if (basum > removal && removal > 0 && i == 0)
{
        batarg = basum - removal;
        treestarg = (batarg / treev[k][4]) *
                treev[k][2];

        i = i + 1;

        species = static_cast <int> (treev[k][0]);
        crown = fcrown(treev[k][3], ccfl,
                treev[k][4] - batarg, treev[k][1]);
        pmort = fgrowmort(treev[k][1], crown, site,
                baad);

        if (pmort < 1)
        {
```

```
                pmort = pmort;
        }
        else pmort = 0.95;

        trees = ftrees(treestarg, pmort);
        dbh = fdinc(treev[k][1], crown, site, baad,
                treev[k][4] - batarg);
        height = fhinc(treev[k][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        removal_biomass = fbiomass(treev[k][1],
                treev[k][2] - treestarg);
        mort_trees = treestarg - trees;
        mort_biomass = fbiomass(treev[k][1],
                mort_trees);
        carea = fcarea(dbh, trees);

        fprintf_s (tree2, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees,
                height, ba);

        bio = bio + biomass;
        htsum = htsum + height;
        tpa = tpa + trees;
        baa = baa + ba;
        ccf = ccf + carea;
        removal_bio = removal_bio + removal_biomass;
        mort_bio = mort_bio + mort_biomass;
}
else if (basum > removal && removal > 0)
{
        i = i + 1;

        species = static_cast <int> (treev[k][0]);
        crown = fcrown(treev[k][3], ccfl,
                treev[k][4], treev[k][1]);
        pmort = fgrowmort(treev[k][1], crown, site,
                baad);

        if (pmort < 1)
        {
                pmort = pmort;
        }
        else pmort = 0.95;

        trees = ftrees(treev[k][2], pmort);
        dbh = fdinc(treev[k][1], crown, site, baad,
                treev[k][4]);
        height = fhinc(treev[k][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        mort_trees = treev[k][2] - trees;
        mort_biomass = fbiomass(treev[k][1],
                mort_trees);
        carea = fcarea(dbh, trees);

        fprintf_s (tree2, "\n %i %i %lf %lf %lf
                %lf", st, species, dbh, trees,
```

```
                        height, ba);

                bio = bio + biomass;
                htsum = htsum + height;
                tpa = tpa + trees;
                baa = baa + ba;
                ccf = ccf + carea;
                mort_bio = mort_bio + mort_biomass;
        }
}

if (rtrees > 0)
{
        i = i + 1;
}

ht = htsum / i;
cr = fcr(ht, baa);
qmd = fqmd(baa, tpa);
sdi = fsdi(qmd, tpa);
mort_bio = (mort_bio  + scan_mort_bio) * (1 - decay_mort *
        decay_horizon);
bio = bio + mort_bio;
delta_bio = bio - scan_bio;

fprintf_s (tree2, "\n %i", endofrecord);
fprintf_s (stand2, "\n %i %i %i %i %lf %lf %lf %lf %lf %lf
        %lf %lf %lf %lf %lf", scan_st, st, j, fire, baa,
        bio, sdi, ccf,removal, delta_bio, removal_bio,
        mort_bio, fmort_bio, fmort_area, sprs_cost);


st = st + 1;
fire = 1;
rd = frd(sdi, SDImax);

if (j == 0)
{
        if (rd >= 0.4)
        {
                if (qmd > 5)
                {
                        fmort = ftl3(ht, cr);
                        fmort_area = ftl3area(road_loc,
                                stand_dtr);
                        sprs_cost = ftl3cost(road_loc,
                                stand_dtr);
                }
                else
                {
                        fmort = fsh4(ht, cr);
                        fmort_area = fsh4area(road_loc,
                                stand_dtr);
                        sprs_cost = fsh4cost(road_loc,
                                stand_dtr);
                }
        }
        else
```

```
                {
                        if (qmd > 9)
                        {
                                fmort = fsb1(ht, cr);
                                fmort_area = fsb1area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsb1cost(road_loc,
                                        stand_dtr);
                        }
                        else if (qmd <= 5)
                        {
                                fmort = ftu5(ht, cr);
                                fmort_area = ftu5area(road_loc,
                                        stand_dtr);
                                sprs_cost = ftu5cost(road_loc,
                                        stand_dtr);
                        }
                        else
                        {
                                fmort = fsh4(ht, cr);
                                fmort_area = fsh4area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsh4cost(road_loc,
                                        stand_dtr);
                        }
                }
        }
        else
        {
                if (rd >= 0.4)
                {
                        if (qmd > 5)
                        {
                                fmort = ftu1(ht, cr);
                                fmort_area = ftu1area(road_loc,
                                        stand_dtr);
                                sprs_cost = ftu1cost(road_loc,
                                        stand_dtr);
                        }
                        else
                        {
                                fmort = fsh6(ht, cr);
                                fmort_area = fsh6area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsh6cost(road_loc,
                                        stand_dtr);
                        }
                }
                else
                {
                        if (qmd > 9)
                        {
                                fmort = fsb2(ht, cr);
                                fmort_area = fsb2area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsb2cost(road_loc,
                                        stand_dtr);
                        }
```

```
                                        else if (qmd <= 5)
                                        {
                                                fmort = fsh5(ht, cr);
                                                fmort_area = fsh5area(road_loc,
                                                        stand_dtr);
                                                sprs_cost = fsh5cost(road_loc,
                                                        stand_dtr);
                                        }
                                        else
                                        {
                                                fmort = fsh6(ht, cr);
                                                fmort_area = fsh6area(road_loc,
                                                        stand_dtr);
                                                sprs_cost = fsh6cost(road_loc,
                                                        stand_dtr);
                                        }
                                }
                        }

                        if (fmort > 0)
                        {

                                bio = 0;
                                removal_bio = 0;
                                mort_bio = 0;
                                fmort_bio = 0;
                                basum = 0;
                                baa = 0;
                                tpa = 0;
                                baad = scan_baa;
                                ccf = 0;
                                ccfl = scan_ccf;

                                i = 0;

//REGENERATION
                                rtrees = frtrees(scan_sdi, SDImax) * (1 - fmort);

                                if (rtrees > 0)
                                {
                                        rba = fba(rdbh, rtrees);

                                        fprintf_s (tree2, "\n %i %i %lf %lf %lf
                                                %lf", st, rspecies, rdbh, rtrees,
                                                rheight, rba);

                                        biomass = fbiomass(rdbh, rtrees);
                                        bio = bio + biomass;
                                        tpa = tpa + rtrees;
                                        baa = baa + rba;
                                        carea = fcarea(rdbh, rtrees);
                                        ccf = ccf + carea;
                                }
//END Regeneration

                                for (int m = 0; m < static_cast <double>
                                        (treev.size()); m++)
                                {
```

```
baad = baad - treev[m][4];
sccarea = fcarea(treev[m][1], treev[m][2]);
ccfl = ccfl - sccarea;

basum = treev[m][4] + basum;

if (removal == 0)
{
       i = i + 1;

       species = static_cast <int>
              (treev[m][0]);
       crown = fcrown(treev[m][3], ccfl,
              treev[m][4], treev[m][1]);
       pmort = fgrowmort(treev[m][1], crown,
              site, baad);

       if (scan_sdi > SDImax)
       {
              sdi_qmd = fqmd(scan_baa,
                     sdi_tpa);
              sdi_treestarg =
                     fsditrees(sdi_qmd,
                     SDImax);

              pmort = pmort + ((sdi_tpa –
                     sdi_treestarg) /
                     sdi_tpa);
       }
       else pmort = pmort;

       if (pmort < 1)
       {
              pmort = pmort;
       }
       else pmort = 0.95;

       trees1 = ftrees(treev[m][2], pmort) *
              ((stand_area - fmort_area) /
              stand_area);
       trees = ftrees(treev[m][2], fmort) *
              (fmort_area / stand_area);
       dbh = fdinc(treev[m][1], crown, site,
              baad, treev[m][4]);
       height = fhinc(treev[m][3], site);
       ba1 = fba(dbh, trees1);
       ba = fba(dbh, trees);
       biomass1 = fbiomass(dbh, trees1);
       biomass = fbiomass(dbh, trees);
       fmort_trees = treev[m][2] *
              (fmort_area / stand_area) –
              trees;
       fmort_biomass = fbiomass(treev[m][1],
              fmort_trees);

       mort_trees = treev[m][2] *
              ((stand_area - fmort_area) /
              stand_area) - trees1;
```

```
        mort_biomass = fbiomass(treev[m][1],
               mort_trees);
        carea1 = fcarea(dbh, trees1);
        carea = fcarea(dbh, trees);

        fprintf_s (tree2, "\n %i %i %lf %lf
               %lf %lf", st, species, dbh,
               trees1, height, ba1);
        fprintf_s (tree2, "\n %i %i %lf %lf
               %lf %lf", st, species, dbh,
               trees, height, ba);

bio = bio + biomass1 + biomass;
        htsum = htsum + height;
        tpa = tpa + trees1 + trees;
        baa = baa + ba1 + ba;
        ccf = ccf + carea1 + carea;
        mort_bio = mort_bio + mort_biomass;

        fmort_bio = fmort_bio +
               fmort_biomass;
}
if (basum <= removal)
{
        removal_biomass =
               fbiomass(treev[m][1],
               treev[m][2]);
        removal_bio = removal_bio +
               removal_biomass;
}
if (basum > removal && removal > 0 && i ==
        0)
{
        batarg = basum - removal;
        treestarg =  (batarg / treev[m][4]) *
               treev[m][2];

        i = i + 1;

        species = static_cast <int>
               (treev[m][0]);
        crown = fcrown(treev[m][3], ccfl,
               treev[m][4] - batarg,
               treev[m][1]);
        pmort = fgrowmort(treev[m][1], crown,
               site, baad);

        if (pmort < 1)
        {
               pmort = pmort;
        }
        else pmort = 0.95;

        trees1 = ftrees(treestarg, pmort) *
               ((stand_area - fmort_area) /
               stand_area);
        trees = ftrees(treestarg, fmort) *
               (fmort_area / stand_area);
```

```
        dbh = fdinc(treev[m][1], crown, site,
               baad, treev[m][4] - batarg);
        height = fhinc(treev[m][3], site);
        ba1 = fba(dbh, trees1);
        ba = fba(dbh, trees);
        biomass1 = fbiomass(dbh, trees1);
        biomass = fbiomass(dbh, trees);
        removal_biomass =
               fbiomass(treev[m][1],
               treev[m][2] - treestarg);
        fmort_trees = treestarg * (fmort_area
               / stand_area) - trees;
        fmort_biomass = fbiomass(treev[m][1],
               fmort_trees);
        mort_trees = treestarg * ((stand_area
               - fmort_area) / stand_area) –
               trees1;
        mort_biomass = fbiomass(treev[m][1],
               mort_trees);
        carea1 = fcarea(dbh, trees1);
        carea = fcarea(dbh, trees);

        fprintf_s (tree2, "\n %i %i %lf %lf
               %lf %lf", st, species, dbh,
               trees1, height, ba1);
        fprintf_s (tree2, "\n %i %i %lf %lf
               %lf %lf", st, species, dbh,
               trees, height, ba);

        bio = bio + biomass1 + biomass;
        htsum = htsum + height;
        tpa = tpa + trees1 + trees;
        baa = baa + ba1 + ba;
        ccf = ccf + carea1 + carea;
        removal_bio = removal_bio +
               removal_biomass;
        mort_bio = mort_bio + mort_biomass;

        fmort_bio = fmort_bio +
               fmort_biomass;
}
else if (basum > removal && removal > 0)
{
        i = i + 1;

        species = static_cast <int>
               (treev[m][0]);
        crown = fcrown(treev[m][3], ccfl,
               treev[m][4], treev[m][1]);
        pmort = fgrowmort(treev[m][1], crown,
               site, baad);

        if (pmort < 1)
        {
               pmort = pmort;
        }
        else pmort = 0.95;
```

```
                trees1 = ftrees(treev[m][2], pmort) *
                       ((stand_area - fmort_area) /
                       stand_area);
                trees = ftrees(treev[m][2], fmort) *
                       (fmort_area / stand_area);
                dbh = fdinc(treev[m][1], crown, site,
                       baad, treev[m][4]);
                height = fhinc(treev[m][3], site);
                ba1 = fba(dbh, trees1);
                ba = fba(dbh, trees);
                biomass1 = fbiomass(dbh, trees1);
                biomass = fbiomass(dbh, trees);
                fmort_trees = treev[m][2] *
                       (fmort_area / stand_area) –
                       trees;
                fmort_biomass = fbiomass(treev[m][1],
                       fmort_trees);

                mort_trees = treev[m][2] *
                       ((stand_area - fmort_area) /
                       stand_area) - trees1;
                mort_biomass = fbiomass(treev[m][1],
                       mort_trees);
                carea1 = fcarea(dbh, trees1);
                carea = fcarea(dbh, trees);

                fprintf_s (tree2, "\n %i %i %lf %lf
                       %lf %lf", st, species, dbh,
                       trees1, height, ba1);
                fprintf_s (tree2, "\n %i %i %lf %lf
                       %lf %lf", st, species, dbh,
                       trees, height, ba);

                bio = bio + biomass1 + biomass;
                htsum = htsum + height;
                tpa = tpa + trees1 + trees;
                baa = baa + ba1 + ba;
                ccf = ccf + carea1 + carea;
                mort_bio = mort_bio + mort_biomass;

                fmort_bio = fmort_bio +
                       fmort_biomass;
        }
}

qmd =fqmd(baa, tpa);
sdi = fsdi(qmd, tpa);
mort_bio = (mort_bio + scan_mort_bio) * (1 –
       decay_mort * decay_horizon);
fmort_bio = fmort_bio * (1 - release_fmort) +
       (scan_fmort_bio * (1 - decay_mort *
       decay_horizon));
bio = bio + mort_bio + fmort_bio;
delta_bio = bio - scan_bio;

fprintf_s (tree2, "\n %i", endofrecord);
fprintf_s (stand2, "\n %i %i %i %i %lf %lf %lf %lf
       %lf %lf %lf %lf %lf %lf %lf", scan_st, st,
```

```
                                j, fire, baa, bio, sdi, ccf,removal,
                                delta_bio, removal_bio, mort_bio, fmort_bio,
                                fmort_area, sprs_cost);

                        st = st + 1;

                }       //END OF FIRE SIMULATION I/O

                redux = redux + redux_incr;

                if (scan_sdi <= SDImax * 0.1)
                {
                        break;
                }
        }
}
fclose(tree1);
fclose(stand1);

//START STAGE 2 to 3 operations

        fopen_s (&stand1, "stage_3.txt", "a+");
        rewind (stand2);
        fopen_s (&tree1, "treelist_3.txt", "a+");
        rewind (tree2);

        //return stage 3 output//

        fclose(tree2);
        fclose(stand2);

//START STAGE 3 to 4 operations

        fopen_s (&stand2, "stage_4.txt", "a+");
        rewind (stand1);
        fopen_s (&tree2, "treelist_4.txt", "a+");
        rewind (tree1);

        //return stage 4 output//

        fclose(tree1);
        fclose(stand1);

//START STAGE 4 to 5 operations

        fopen_s (&stand1, "stage_5.txt", "a+");
        rewind (stand2);
        fopen_s (&tree1, "treelist_5.txt", "a+");
        rewind (tree2);

        //return stage 5 output//

        fclose(tree2);
        fclose(stand2);

//START STAGE 5 to 6 operations

        fopen_s (&stand2, "stage_6.txt", "a+");
```

```
        rewind (stand1);
        fopen_s (&tree2, "treelist_6.txt", "a+");
        rewind (tree1);

        //return stage 6 output//

        fclose(tree1);
        fclose(stand1);

//START STAGE 6 to 7 operations

        fopen_s (&stand1, "stage_7.txt", "a+");
        rewind (stand2);
        fopen_s (&tree1, "treelist_7.txt", "a+");
        rewind (tree2);
        cout << "State Space 7: " << st << endl;

        fclose(tree2);
        fclose(stand2);

//START STAGE 7 to 8 operations

        fopen_s (&stand2, "stage_8.txt", "a+");
        rewind (stand1);
        fopen_s (&tree2, "treelist_8.txt", "a+");
        rewind (tree1);

        //return stage 8 output//

        fclose(tree1);
        fclose(stand1);

//START STAGE 8 to 9 operations

        fopen_s (&stand1, "stage_9.txt", "a+");
        rewind (stand2);
        fopen_s (&tree1, "treelist_9.txt", "a+");
        rewind (tree2);

        //return stage 9 output//

        fclose(tree2);
        fclose(stand2);

//START STAGE 9 to 10 operations

        fopen_s (&stand2, "stage_99.txt", "a+");
        rewind (stand1);
        rewind (tree1);

        st = 0;

        while (!feof (stand1))
        {
                fscanf_s (stand1, "%i %i %i %i %lf %lf %lf %lf %lf %lf %lf %lf
                        %lf %lf %lf", &scan_prev_stg_st, &scan_st, &scan_j,
                        &scan_fire, &scan_baa, &scan_bio, &scan_sdi, &scan_ccf,
                        &scan_removal, &scan_delta_bio, &scan_removal_bio,
```

```
            &scan_mort_bio, &scan_fmort_bio, &scan_fmort_area,
            &scan_sprs_cost);

        sdi_tpa = 0;
        redux = 0;

        vector< vector<double> > treev;

        fgetpos (tree1, &pos);

        goto label_17;

label_17: fsetpos (tree1, &pos);

        fscanf_s (tree1, "%i", &eomegarec);

        if (eomegarec >= 0)
        {
            fscanf_s (tree1, "%i %lf %lf %lf %lf", &species,
                &scan_dbh, &scan_trees, &scan_height, &scan_ba);

            sdi_tpa = sdi_tpa + scan_trees;

            vector<double> row(5);

            row[0] = species;
            row[1] = scan_dbh;
            row[2] = scan_trees;
            row[3] = scan_height;
            row[4] = scan_ba;

            treev.push_back(row);

            fscanf_s (tree1, "\n");
            fgetpos (tree1, &pos);
            goto label_17;
        }
        else
        {
            fscanf_s (tree1, "\n");
            fgetpos (tree1, &pos);
            goto label_18;
        }

label_18: for (int j = 0; j < treat_no; j++)
            {
                fire = 0;
                baatarg = fbatarget(scan_baa, redux);
                removal = scan_baa - baatarg;

                bio = 0;
                removal_bio = 0;
                mort_bio = 0;
                fmort_bio = 0;
                fmort_area = 0;
                sprs_cost = 0;
                basum = 0;
                baa = 0;
```

```
                            tpa = 0;
                            htsum = 0;
                            baad = scan_baa;
                            ccf = 0;
                            ccfl = scan_ccf;

                            int i = 0;

//REGENERATION
                            rtrees = frtrees(scan_sdi, SDImax);

                            if (rtrees > 0)
                            {
                                   rba = fba(rdbh, rtrees);
                                   biomass = fbiomass(rdbh, rtrees);
                                   bio = bio + biomass;
                                   htsum = htsum + rheight;
                                   tpa = tpa + rtrees;
                                   baa = baa + rba;
                                   carea = fcarea(rdbh, rtrees);
                                   ccf = ccf + carea;
                            }
//END Regeneration

                            for (int k = 0; k < static_cast <double>
                                   (treev.size()); k++)
                            {
                                   baad = baad - treev[k][4];
                                   sccarea = fcarea(treev[k][1], treev[k][2]);
                                   ccfl = ccfl - sccarea;

                                   basum = treev[k][4] + basum;

                                   if (removal == 0)
                                   {
                                          i = i + 1;

                                          species = static_cast <int>
                                                 (treev[k][0]);
                                          crown = fcrown(treev[k][3], ccfl,
                                                 treev[k][4], treev[k][1]);
                                          pmort = fgrowmort(treev[k][1], crown,
                                                 site, baad);

                                          if (scan_sdi > SDImax)
                                          {
                                                 sdi_qmd = fqmd(scan_baa,
                                                        sdi_tpa);
                                                 sdi_treestarg =
                                                        fsditrees(sdi_qmd,
                                                        SDImax);

                                                 pmort = pmort + ((sdi_tpa –
                                                        sdi_treestarg) /
                                                        sdi_tpa);
                                          }
                                          else pmort = pmort;
```

```
        if (pmort < 1)
        {
               pmort = pmort;
        }
        else pmort = 0.95;

        trees = ftrees(treev[k][2], pmort);
        dbh = fdinc(treev[k][1], crown, site,
               baad, treev[k][4]);
        height = fhinc(treev[k][3], site);
        ba = fba(dbh, trees);
        biomass = fbiomass(dbh, trees);
        mort_trees = treev[k][2] - trees;
        mort_biomass = fbiomass(treev[k][1],
               mort_trees);
        carea = fcarea(dbh, trees);
        bio = bio + biomass;
        htsum = htsum + height;
        tpa = tpa + trees;
        baa = baa + ba;
        ccf = ccf + carea;
        mort_bio = mort_bio + mort_biomass;
}
if (basum <= removal)
{
        removal_biomass =
               fbiomass(treev[k][1],
               treev[k][2]);
        removal_bio = removal_bio +
               removal_biomass;
}
if (basum > removal && removal > 0 && i ==
        0)
{
        batarg = basum - removal;
        treestarg = (batarg / treev[k][4]) *
               treev[k][2];

        i = i + 1;

        species = static_cast <int>
               (treev[k][0]);
        crown = fcrown(treev[k][3], ccfl,
               treev[k][4] - batarg,
               treev[k][1]);
        pmort = fgrowmort(treev[k][1], crown,
               site, baad);

        if (pmort < 1)
        {
               pmort = pmort;
        }
        else pmort = 0.95;

        trees = ftrees(treestarg, pmort);
        dbh = fdinc(treev[k][1], crown, site,
               baad, treev[k][4] - batarg);
        height = fhinc(treev[k][3], site);
```

```
                ba = fba(dbh, trees);
                biomass = fbiomass(dbh, trees);
                removal_biomass =
                        fbiomass(treev[k][1],
                        treev[k][2] - treestarg);
                mort_trees = treestarg - trees;
                mort_biomass = fbiomass(treev[k][1],
                        mort_trees);
                carea = fcarea(dbh, trees);
                bio = bio + biomass;
                htsum = htsum + height;
                tpa = tpa + trees;
                baa = baa + ba;
                ccf = ccf + carea;
                removal_bio = removal_bio +
                        removal_biomass;
                mort_bio = mort_bio + mort_biomass;
        }
        else if (basum > removal && removal > 0)
        {
                i = i + 1;

                species = static_cast <int>
                        (treev[k][0]);
                crown = fcrown(treev[k][3], ccfl,
                        treev[k][4], treev[k][1]);
                pmort = fgrowmort(treev[k][1], crown,
                        site, baad);

                if (pmort < 1)
                {
                        pmort = pmort;
                }
                else pmort = 0.95;

                trees = ftrees(treev[k][2], pmort);
                dbh = fdinc(treev[k][1], crown, site,
                        baad, treev[k][4]);
                height = fhinc(treev[k][3], site);
                ba = fba(dbh, trees);
                biomass = fbiomass(dbh, trees);
                mort_trees = treev[k][2] - trees;
                mort_biomass = fbiomass(treev[k][1],
                        mort_trees);
                carea = fcarea(dbh, trees);
                bio = bio + biomass;
                htsum = htsum + height;
                tpa = tpa + trees;
                baa = baa + ba;
                ccf = ccf + carea;
                mort_bio = mort_bio + mort_biomass;
        }
}

if (rtrees > 0)
{
        i = i + 1;
}
```

```
ht = htsum / i;
cr = fcr(ht, baa);
qmd = fqmd(baa, tpa);
sdi = fsdi(qmd, tpa);
mort_bio = (mort_bio + scan_mort_bio) * (1 –
       decay_mort * decay_horizon);
bio = bio + mort_bio;
delta_bio = bio - scan_bio;

fprintf_s (stand2, "\n %i %i %i %i %lf %lf %lf %lf
       %lf %lf %lf %lf %lf", scan_st, st, j, fire,
       baa, bio, removal, delta_bio, removal_bio,
       mort_bio, fmort_bio, fmort_area, sprs_cost);


st = st + 1;
fire = 1;
rd = frd(sdi, SDImax);

if (j == 0)
{
       if (rd >= 0.4)
       {
              if (qmd > 5)
              {
                     fmort = ftl3(ht, cr);
                     fmort_area = ftl3area(road_loc,
                            stand_dtr);
                     sprs_cost = ftl3cost(road_loc,
                            stand_dtr);
              }
              else
              {
                     fmort = fsh4(ht, cr);
                     fmort_area = fsh4area(road_loc,
                            stand_dtr);
                     sprs_cost = fsh4cost(road_loc,
                            stand_dtr);
              }
       }
       else
       {
              if (qmd > 9)
              {
                     fmort = fsb1(ht, cr);
                     fmort_area = fsb1area(road_loc,
                            stand_dtr);
                     sprs_cost = fsb1cost(road_loc,
                            stand_dtr);
              }
              else if (qmd <= 5)
              {
                     fmort = ftu5(ht, cr);
                     fmort_area = ftu5area(road_loc,
                            stand_dtr);
                     sprs_cost = ftu5cost(road_loc,
                            stand_dtr);
```

```
                        }
                        else
                        {
                                fmort = fsh4(ht, cr);
                                fmort_area = fsh4area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsh4cost(road_loc,
                                        stand_dtr);
                        }
                }
        }
        else
        {
                if (rd >= 0.4)
                {
                        if (qmd > 5)
                        {
                                fmort = ftu1(ht, cr);
                                fmort_area = ftu1area(road_loc,
                                        stand_dtr);
                                sprs_cost = ftu1cost(road_loc,
                                        stand_dtr);
                        }
                        else
                        {
                                fmort = fsh6(ht, cr);
                                fmort_area = fsh6area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsh6cost(road_loc,
                                        stand_dtr);
                        }
                }
                else
                {
                        if (qmd > 9)
                        {
                                fmort = fsb2(ht, cr);
                                fmort_area = fsb2area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsb2cost(road_loc,
                                        stand_dtr);
                        }
                        else if (qmd <= 5)
                        {
                                fmort = fsh5(ht, cr);
                                fmort_area = fsh5area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsh5cost(road_loc,
                                        stand_dtr);
                        }
                        else
                        {
                                fmort = fsh6(ht, cr);
                                fmort_area = fsh6area(road_loc,
                                        stand_dtr);
                                sprs_cost = fsh6cost(road_loc,
                                        stand_dtr);
                        }
```

```
        }
}

if (fmort > 0)
{

        bio = 0;
        removal_bio = 0;
        mort_bio = 0;
        fmort_bio = 0;
        basum = 0;
        baa = 0;
        tpa = 0;
        baad = scan_baa;
        ccf = 0;
        ccfl = scan_ccf;

        i = 0;

//REGENERATION
        rtrees = frtrees(scan_sdi, SDImax) * (1 –
                fmort);

        if (rtrees > 0)
        {
                rba = fba(rdbh, rtrees);
                biomass = fbiomass(rdbh, rtrees);
                bio = bio + biomass;
                tpa = tpa + rtrees;
                baa = baa + rba;
                carea = fcarea(rdbh, rtrees);
                ccf = ccf + carea;
        }
//END Regeneration

        for (int m = 0; m < static_cast <double>
                (treev.size()); m++)
        {
                baad = baad - treev[m][4];
                sccarea = fcarea(treev[m][1],
                        treev[m][2]);
                ccfl = ccfl - sccarea;

                basum = treev[m][4] + basum;

                if (removal == 0)
                {
                        i = i + 1;

                        species = static_cast <int>
                                (treev[m][0]);
                        crown = fcrown(treev[m][3],
                                ccfl, treev[m][4],
                                treev[m][1]);
                        pmort = fgrowmort(treev[m][1],
                                crown, site, baad);

                        if (scan_sdi > SDImax)
```

```
{
	sdi_qmd = fqmd(scan_baa,
		sdi_tpa);
	sdi_treestarg =
		fsditrees(sdi_qmd
		, SDImax);

	pmort = pmort +
		((sdi_tpa –
		sdi_treestarg) /
		sdi_tpa);
}
else pmort = pmort;

if (pmort < 1)
{
	pmort = pmort;
}
else pmort = 0.95;

trees1 = ftrees(treev[m][2],
	pmort) * ((stand_area -
	fmort_area) /
	stand_area);
trees = ftrees(treev[m][2],
	fmort) * (fmort_area /
	stand_area);
dbh = fdinc(treev[m][1], crown,
	site, baad,
	treev[m][4]);
height = fhinc(treev[m][3],
	site);
ba1 = fba(dbh, trees1);
ba = fba(dbh, trees);
biomass1 = fbiomass(dbh,
	trees1);
biomass = fbiomass(dbh, trees);
fmort_trees = treev[m][2] *
	(fmort_area /
	stand_area) - trees;
fmort_biomass =
	fbiomass(treev[m][1],
	fmort_trees);

mort_trees = treev[m][2] *
	((stand_area –
	fmort_area) /
	stand_area) - trees1;
mort_biomass =
	fbiomass(treev[m][1],
	mort_trees);
carea1 = fcarea(dbh, trees1);
carea = fcarea(dbh, trees);
bio = bio + biomass1 + biomass;
htsum = htsum + height;
tpa = tpa + trees1 + trees;
baa = baa + ba1 + ba;
```

```
		ccf = ccf + carea1 + carea;

		mort_bio = mort_bio +
			mort_biomass;
		fmort_bio = fmort_bio +
			fmort_biomass;
	}
	if (basum <= removal)
	{
		removal_biomass =
			fbiomass(treev[m][1],
			treev[m][2]);
		removal_bio = removal_bio +
			removal_biomass;
	}
	if (basum > removal && removal > 0 &&
		i == 0)
	{
		batarg = basum - removal;
		treestarg = (batarg /
		treev[m][4]) * treev[m][2];

		i = i + 1;

		species = static_cast <int>
			(treev[m][0]);
		crown = fcrown(treev[m][3],
			ccfl, treev[m][4] –
			batarg, treev[m][1]);
		pmort = fgrowmort(treev[m][1],
			crown, site, baad);

		if (pmort < 1)
		{
			pmort = pmort;
		}
		else pmort = 0.95;

		trees1 = ftrees(treestarg,
			pmort) * ((stand_area –
			fmort_area) /
			stand_area);
		trees = ftrees(treestarg,
			fmort) * (fmort_area /
			stand_area);
		dbh = fdinc(treev[m][1], crown,
			site, baad, treev[m][4]
			- batarg);
		height = fhinc(treev[m][3],
			site);
		ba1 = fba(dbh, trees1);
		ba = fba(dbh, trees);
		biomass1 = fbiomass(dbh,
			trees1);
		biomass = fbiomass(dbh, trees);
		removal_biomass =
			fbiomass(treev[m][1],
```

```
                        treev[m][2] -
                        treestarg);
                fmort_trees = treestarg *
                        (fmort_area /
                        stand_area) - trees;
                fmort_biomass =
                        fbiomass(treev[m][1],
                        fmort_trees);
                mort_trees = treestarg *
                        ((stand_area –
                        fmort_area) /
                        stand_area) - trees1;
                mort_biomass =
                        fbiomass(treev[m][1],
                        mort_trees);
                carea1 = fcarea(dbh, trees1);
                carea = fcarea(dbh, trees);
                bio = bio + biomass1 + biomass;
                htsum = htsum + height;
                tpa = tpa + trees1 + trees;
                baa = baa + ba1 + ba;
                ccf = ccf + carea1 + carea;

                removal_bio = removal_bio +
                        removal_biomass;
                mort_bio = mort_bio +
                        mort_biomass;
                fmort_bio = fmort_bio +
                        fmort_biomass;
        }
        else if (basum > removal && removal >
                0)
        {
                i = i + 1;

                species = static_cast <int>
                        (treev[m][0]);
                crown = fcrown(treev[m][3],
                        ccfl, treev[m][4],
                        treev[m][1]);
                pmort = fgrowmort(treev[m][1],
                        crown, site, baad);

                if (pmort < 1)
                {
                        pmort = pmort;
                }
                else pmort = 0.95;

                trees1 = ftrees(treev[m][2],
                        pmort) * ((stand_area –
                        fmort_area) /
                        stand_area);
                trees = ftrees(treev[m][2],
                        fmort) * (fmort_area /
                        stand_area);
                dbh = fdinc(treev[m][1], crown,
                        site, baad,
```

```
                    treev[m][4]);
                height = fhinc(treev[m][3],
                    site);
                ba1 = fba(dbh, trees1);
                ba = fba(dbh, trees);
                biomass1 = fbiomass(dbh,
                    trees1);
                biomass = fbiomass(dbh, trees);

                fmort_trees = treev[m][2] *
                    (fmort_area /
                    stand_area) - trees;
                fmort_biomass =
                    fbiomass(treev[m][1],
                    fmort_trees);

                mort_trees = treev[m][2] *
                    ((stand_area –
                    fmort_area) /
                    stand_area) - trees1;
                mort_biomass =
                    fbiomass(treev[m][1],
                    mort_trees);
                carea1 = fcarea(dbh, trees1);
                carea = fcarea(dbh, trees);
                bio = bio + biomass1 + biomass;
                htsum = htsum + height;
                tpa = tpa + trees1 + trees;
                baa = baa + ba1 + ba;
                ccf = ccf + carea1 + carea;

                mort_bio = mort_bio +
                    mort_biomass;
                fmort_bio = fmort_bio +
                    fmort_biomass;
            }
        }

        qmd = fqmd(baa, tpa);
        sdi = fsdi(qmd, tpa);
        mort_bio = (mort_bio + scan_mort_bio) * (1 –
            decay_mort * decay_horizon);
        fmort_bio = fmort_bio * (1 - release_fmort)
            + (scan_fmort_bio * (1 - decay_mort *
            decay_horizon));
        bio = bio + mort_bio + fmort_bio;
        delta_bio = bio - scan_bio;

        fprintf_s (stand2, "\n %i %i %i %i %lf %lf
            %lf %lf %lf %lf %lf %lf %lf",
            scan_st, st, j, fire, baa, bio,
            removal, delta_bio, removal_bio,
            mort_bio, fmort_bio, fmort_area,
            sprs_cost);

        st = st + 1;

    }   //END OF FIRE SIMULATION I/O
```

```
                            redux = redux + redux_incr;

                            if (scan_sdi <= SDImax * 0.1)
                            {
                                   break;
                            }
                     }
       }
       fclose(tree1);

//EXPECTED CARBON VALUE @ END OF FINAL STAGE==99

       fopen_s (&C99, "C_99.txt", "w+");
       rewind (stand2);
       fgetpos(stand2, &pos);

       while (!feof (stand2))
       {
              goto label_19;

label_19: fsetpos (stand2, &pos);

              fscanf_s (stand2, "%i %i %i %i %lf %lf %lf %lf %lf %lf %lf %lf
                     %lf", &scan_prev_stg_st, &scan_st, &scan_j, &scan_fire,
                     &scan_baa, &scan_bio, &scan_removal, &scan_delta_bio,
                     &scan_removal_bio, &scan_mort_bio, &scan_fmort_bio,
                     &scan_fmort_area, &scan_sprs_cost);

              fgetpos (stand2, &pos);

              C = scan_bio * Cf;

              fscanf_s (stand2, "\n");

              if (feof(stand2))
              {
                     fprintf_s (C99, "\n %i %i %i %lf %lf %lf %lf %lf",
                            scan_prev_stg_st, scan_st, scan_j, scan_removal,
                            scan_removal_bio, scan_fmort_area, scan_sprs_cost,
                            C);
                     break;
              }

              fscanf_s (stand2, "%i %i %i %i", &scan_prev_stg_st_1, &scan_st_1,
                     &scan_j_1, &scan_fire_1);

              if (scan_fire_1 == 0)
              {
                     fprintf_s (C99, "\n %i %i %i %lf %lf %lf %lf %lf",
                            scan_prev_stg_st, scan_st, scan_j, scan_removal,
                            scan_removal_bio, scan_fmort_area, scan_sprs_cost,
                            C);

                     goto label_19;
              }
              else if (scan_fire_1 == 1)
              {
                     fscanf_s (stand2, "%lf %lf %lf %lf %lf %lf %lf %lf %lf",
```

```
                        &scan_baa_1, &scan_bio_1, &scan_removal_1,
                        &scan_delta_bio_1, &scan_removal_bio_1,
                        &scan_mort_bio_1, &scan_fmort_bio_1,
                        &scan_fmort_area_1, &scan_sprs_cost_1);

                fgetpos (stand2, &pos);

                C_1 = scan_bio_1 * Cf;
                Cp = C * (1 - P_fire) + C_1 * P_fire;

                fprintf_s (C99, "\n %i %i %i %lf %lf %lf %lf %lf",
                        scan_prev_stg_st, scan_st, scan_j, scan_removal,
                        scan_removal_bio, scan_fmort_area_1,
                        scan_sprs_cost_1, Cp);

                goto label_19;
            }
        }
        fclose (stand2);

//START OF MAX CARBON @ START OF STAGE 9

        fopen_s (&C1, "C_9.txt", "w+");
        rewind (C99); //INPUT

        stage_no = 9;
        Dhorizon = (100 - stage_length * stage_no);

        fgetpos(C99, &pos);

        while (!feof (C99))
        {
            CCCmax = 0;

            goto label_20;

label_20: fsetpos (C99, &pos);

            fscanf_s (C99, "%i %i %i %lf %lf %lf %lf %lf",
                &scan_Cprev_stg_st, &scan_Cst, &scan_Cj, &scan_Cremoval,
                &scan_Cremoval_bio, &scan_Cfmort_area, &scan_Csprs_cost,
                &scan_Cp);

            fgetpos (C99, &pos);

            CCC = obj_funk(scan_Cremoval_bio, Cf, Dhorizon, Ur, nUr, USTd,
                Pd, CWDd, scan_Cp);
            CCCmax = max (CCCmax, CCC);

            if (CCC == CCCmax)
            {
                prev_stg_st = scan_Cprev_stg_st;
                st = scan_Cst;
                j = scan_Cj;
                removal = scan_Cremoval;
                removal_bio = scan_Cremoval_bio;
                fmort_area = scan_Cfmort_area;
                sprs_cost = scan_Csprs_cost * P_fire;
```

```
            }

            fscanf_s (C99, "%i", &state);

            if (feof(C99))
            {
                  fprintf_s (C1, "\n %i %i %i %lf %lf %lf %lf %lf",
                        prev_stg_st, st, j, removal, removal_bio,
                        fmort_area, sprs_cost, CCCmax);
                  break;
            }

            if (state == scan_Cprev_stg_st)
            {
                  goto label_20;
            }
            else fprintf_s (C1, "\n %i %i %i %lf %lf %lf %lf %lf",
                  prev_stg_st, st, j, removal, removal_bio, fmort_area,
                  sprs_cost, CCCmax);

//START OF MAX CARBON @ START OF STAGE 8

      fopen_s (&C2, "C_8.txt", "w+");
      rewind (C1);
      rewind (stand1);

      stage_no = 8;

      //return MAX C @ stage 8

      fclose (C1);
      fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 7

      fopen_s (&C1, "C_7.txt", "w+");
      rewind (C2);
      fopen_s (&stand1, "stage_8.txt", "r+");

      stage_no = 7;

      //return MAX C @ stage 7

      fclose (C2);
      fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 6

      fopen_s (&C2, "C_6.txt", "w+");
      rewind (C1);
      fopen_s (&stand1, "stage_7.txt", "r+");

      stage_no = 6;

      //return MAX C @ stage 6

      fclose (C1);
      fclose (stand1);
```

```
//START OF MAX CARBON @ START OF STAGE 5

       fopen_s (&C1, "C_5.txt", "w+");
       rewind (C2);
       fopen_s (&stand1, "stage_6.txt", "r+");

       stage_no = 5;

       //return MAX C @ stage 5

       fclose (C2);
       fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 4

       fopen_s (&C2, "C_4.txt", "w+");
       rewind (C1);
       fopen_s (&stand1, "stage_5.txt", "r+");

       stage_no = 4;

       //return MAX C @ stage 4

       fclose (C1);
       fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 3

       fopen_s (&C1, "C_3.txt", "w+");
       rewind (C2);
       fopen_s (&stand1, "stage_4.txt", "r+");

       stage_no = 3;

       //return MAX C @ stage 3

       fclose (C2);
       fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 2

       fopen_s (&C2, "C_2.txt", "w+");
       rewind (C1);
       fopen_s (&stand1, "stage_3.txt", "r+");

       stage_no = 2;

       //return MAX C @ stage 2

       fclose (C1);
       fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 1

       fopen_s (&C1, "C_1.txt", "w+");
       rewind (C2);
       fopen_s (&stand1, "stage_2.txt", "r+");
```

```
        stage_no = 1;

        //return MAX C @ stage 1

        fclose (C2);
        fclose (stand1);

//START OF MAX CARBON @ START OF STAGE 0

        fopen_s (&C2, "C_0.txt", "w+");
        rewind (C1);
        fopen_s (&stand1, "stage_1.txt", "r+");

        stage_no = 0;

        //return MAX C @ stage 0

        fclose (C1);
        fclose (C2);
        fclose (stand1);

//START OF OPTIMAL PATH SEARCH

        fopen_s (&C2, "pathway.txt", "w+");
        fopen_s (&C1, "C_0.txt", "r+");

        fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
                &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
                &scan_fmort_area, &scan_sprs_cost, &scan_Cp);

        st = scan_st;

        fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j, scan_removal,
                scan_removal_bio, scan_fmort_area, scan_sprs_cost, scan_Cp);
        fclose (C1);

        fopen_s (&C1, "C_1.txt", "r+");

        while (!feof (C1))
        {
                fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
                        &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
                        &scan_fmort_area, &scan_sprs_cost, &scan_Cp);

                if (scan_prev_stg_st == st)
                {
                        st = scan_st;

                        fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
                                scan_removal, scan_removal_bio, scan_fmort_area,
                                scan_sprs_cost, scan_Cp);
                        fclose (C1);
                        break;
                }
        }

        fopen_s (&C1, "C_2.txt", "r+");
```

```
while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_fmort_area, &scan_sprs_cost, &scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;

		fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_fmort_area,
			scan_sprs_cost, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_3.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_fmort_area, &scan_sprs_cost, &scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;

		fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_fmort_area,
			scan_sprs_cost, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_4.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_fmort_area, &scan_sprs_cost, &scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;

		fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_fmort_area,
			scan_sprs_cost, scan_Cp);
		fclose (C1);
		break;
	}
}
```

```
fopen_s (&C1, "C_5.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_fmort_area, &scan_sprs_cost, &scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;

		fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_fmort_area,
			scan_sprs_cost, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_6.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_fmort_area, &scan_sprs_cost, &scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;

		fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_fmort_area,
			scan_sprs_cost, scan_Cp);
		fclose (C1);
		break;
	}
}

fopen_s (&C1, "C_7.txt", "r+");

while (!feof (C1))
{
	fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
		&scan_st, &scan_j, &scan_removal, &scan_removal_bio,
		&scan_fmort_area, &scan_sprs_cost, &scan_Cp);

	if (scan_prev_stg_st == st)
	{
		st = scan_st;

		fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
			scan_removal, scan_removal_bio, scan_fmort_area,
			scan_sprs_cost, scan_Cp);
		fclose (C1);
		break;
	}
```

```
}

fopen_s (&C1, "C_8.txt", "r+");

while (!feof (C1))
{
       fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
              &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
              &scan_fmort_area, &scan_sprs_cost, &scan_Cp);

       if (scan_prev_stg_st == st)
       {
              st = scan_st;

              fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
                     scan_removal, scan_removal_bio, scan_fmort_area,
                     scan_sprs_cost, scan_Cp);
              fclose (C1);
              break;
       }
}

fopen_s (&C1, "C_9.txt", "r+");

while (!feof (C1))
{
       fscanf_s (C1, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
              &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
              &scan_fmort_area, &scan_sprs_cost, &scan_Cp);

       if (scan_prev_stg_st == st)
       {
              st = scan_st;

              fprintf_s (C2, "\n %i %i %lf %lf %lf %lf %lf", st, scan_j,
                     scan_removal, scan_removal_bio, scan_fmort_area,
                     scan_sprs_cost, scan_Cp);
              fclose (C1);
              break;
       }
}

rewind (C99);

while (!feof (C99))
{
       fscanf_s (C99, "%i %i %i %lf %lf %lf %lf %lf", &scan_prev_stg_st,
              &scan_st, &scan_j, &scan_removal, &scan_removal_bio,
              &scan_fmort_area, &scan_sprs_cost, &scan_Cp);

       if (scan_st == st)
       {
              fprintf_s (C2, "\n %lf %lf", scan_sprs_cost, scan_Cp);
              fclose (C99);
              break;
       }
}
fclose (C2);
```

```
return 0;
}

double fsditrees (double xqmd, int xSDImax)
       {
              return xSDImax * pow ((xqmd / 10), -1.605);
       }

double frd (double xsdi, int xSDImax)
       {
              return xsdi / xSDImax;
       }

double fcr (double xht, double xbaa)
       {
              return (xht - (-1.771 + 0.554 * xht + 0.045 * xbaa)) /
                     xht;
       }

double fcarea (double xdbh, double xtrees)
       {
              return 3.14159 * ((1.6654 + 0.0355 * xdbh) * (1.6654 +
                     0.0355 * xdbh)) * 0.0023 * xtrees;
       }

double fbatarget (double xbaa, double xredux)
       {
              return (xbaa * (1 - xredux));
       }

double fcrown (double xheight, double xccfl, double xba, double xdbh)
       {
              return 1 - (1 / (1 + exp(1.94093 - 0.0065029 * xheight –
                     0.0048737 * xccfl - 0.261573 * log(xba) + 1.08785 *
                     xdbh / xheight)));
       }

double ftrees (double xtrees, double xmort)
       {
              return xtrees * (1 - xmort);
       }

double frtrees (double xsdi, int xSDImax)
       {
              return 20 * (1 - (xsdi / xSDImax));
       }

double fba (double xdbh, double xtrees)
       {
              return 0.005454 * (xdbh * xdbh) * xtrees;
       }

double fbiomass (double xdbh, double xtrees)
       {
              return 0.0011231131 * (0.0808 * pow ((xdbh * 2.54),
                     2.5282)) * xtrees;
       }
double fqmd (double xbaa, double xtpa)
```

```
        {
                return pow (xbaa /(0.005454 * xtpa), 0.5);
        }

double fsdi (double xqmd, double xtpa)
        {
                return xtpa * pow ((xqmd / 10), 1.605);
        }

double fdinc (double xdbh, double xcrown, double xsite, double xbaad,
        double xba)
        {
                return 2.01 * (exp(- 4.69624 + 0.339513 * log (xdbh + 1) –
                        0.00042826 * (xdbh * xdbh) + 1.19952 * log ((xcrown
                        + 0.2) / 1.2) + 1.15612 * log (xsite - 4.5) –
                        0.0000446327 * (xbaad * xbaad) / log (xdbh + 5) –
                        0.0237003 * sqrt (xba))) + xdbh;
        }

double fhinc (double xheight, double xsite)
        {
                double gea; //growth effective age

                gea = pow ((log (1 - ((xheight - 4.5) / (xsite - 4.5)) *
                        (1 - exp (-0.00199536 * pow (xsite - 4.5, 0.281176)
                        * pow (50, 1.14354))))) / (-0.00199536 * pow (xsite
                        - 4.5, 0.281176)), 1 / 1.14354);

                return 1.95 * ((4.5 + (xheight - 4.5) * ((1 - exp (-
                        0.00199536 * pow (xsite - 4.5, 0.281176) * pow (gea
                        + 5, 1.14354))) / (1 - exp (-0.00199536 * pow
                        (xsite - 4.5, 0.281176) * pow (gea, 1.14354))))) –
                        xheight) + xheight;
        }

double fgrowmort (double xdbh, double xcrown, double xsite, double
        xbaad)
        {
                return (1.9 * (1 / (1 + exp(-(-0.149558 - 0.203923 * xdbh
                        - 7.32001 * xcrown + 0.0133533 * xsite + 0.00168508
                        * xbaad))))) / 100;
        }

double fsh4 (double xht, double xcr)
{
        if (xht > 100)
        {
                if (xht <= 125)
                {
                        if (xcr > 0.8)
                        {
                                return 0.93;
                        }
                        else if (0.7 < xcr && xcr <= 0.8)
                        {
                                return 0.90;
                        }
                        else if (0.6 < xcr && xcr <= 0.7)
```

```
        {
            return 0.84;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
            return 0.71;
        }
        else if (0.4 < xcr && xcr <= 0.5)
        {
            return 0.50;
        }
        else if (0.3 < xcr && xcr <= 0.4)
        {
            return 0.34;
        }
        else return 0;
    }
    else if (125 < xht && xht <= 150)
    {
        if (xcr > 0.8)
        {
            return 0.72;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
            return 0.60;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
            return 0.45;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
            return 0.35;
        }
        else if (0.4 < xcr && xcr <= 0.5)
        {
            return 0.29;
        }
        else return 0;
    }
    else if (150 < xht && xht <= 175)
    {
        if (xcr > 0.8)
        {
            return 0.50;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
            return 0.40;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
            return 0.34;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
            return 0.28;
```

```
				}
				else return 0;
			}
			else
			{
				if (xcr > 0.8)
				{
					return 0.39;
				}
				else if (0.7 < xcr && xcr <= 0.8)
				{
					return 0.34;
				}
				else if (0.6 < xcr && xcr <= 0.7)
				{
					return 0.31;
				}
				else return 0;
			}
		}
		else return 0.98;
	}

	double fsh5 (double xht, double xcr)
	{
		if (xht > 0 && xcr > 0)
		{
			return 0.98;
		}
	}

	double fsh6 (double xht, double xcr)
	{
		if (xht > 150)
		{
			if (xht <= 175)
			{
				if (xcr > 0.8)
				{
					return 0.95;
				}
				else if (0.7 < xcr && xcr <= 0.8)
				{
					return 0.93;
				}
				else if (0.6 < xcr && xcr <= 0.7)
				{
					return 0.90;
				}
				else if (0.5 < xcr && xcr <= 0.6)
				{
					return 0.83;
				}
				else if (0.4 < xcr && xcr <= 0.5)
				{
					return 0.67;
				}
				else if (0.3 < xcr && xcr <= 0.4)
```

```
                        {
                                return 0.41;
                        }
                        else return 0.24;
                }
                else
                {
                        if (xcr > 0.8)
                        {
                                return 0.85;
                        }
                        else if (0.7 < xcr && xcr <= 0.8)
                        {
                                return 0.77;
                        }
                        else if (0.6 < xcr && xcr <= 0.7)
                        {
                                return 0.64;
                        }
                        else if (0.5 < xcr && xcr <= 0.6)
                        {
                                return 0.47;
                        }
                        else if (0.4 < xcr && xcr <= 0.5)
                        {
                                return 0.34;
                        }
                        else if (0.3 < xcr && xcr <= 0.4)
                        {
                                return 0.19;
                        }
                        else return 0;
                }
        }
        else return 0.98;
}

double fsb1 (double xht, double xcr)
{
        if (xht <= 100)
        {
                if (xht > 75)
                {
                        if (xcr > 0.8)
                        {
                                return 0.17;
                        }
                        else return 0;
                }
                else if (xht > 50)
                {
                        if (xcr > 0.8)
                        {
                                return 0.29;
                        }
                        else return 0;
                }
                else
```

```
		{
			if (xcr > 0.8)
			{
				return 0.35;
			}
			else if (0.7 < xcr && xcr <= 0.8)
			{
				return 0.32;
			}
			else if (0.6 < xcr && xcr <= 0.7)
			{
				return 0.24;
			}
			else return 0;
		}
	}
	else return 0;
}

double fsb2 (double xht, double xcr)
{
	if (xht > 75)
	{
		if (xht <= 100)
		{
			if (xcr > 0.8)
			{
				return 0.91;
			}
			else if (0.7 < xcr && xcr <= 0.8)
			{
				return 0.86;
			}
			else if (0.6 < xcr && xcr <= 0.7)
			{
				return 0.78;
			}
			else if (0.5 < xcr && xcr <= 0.6)
			{
				return 0.62;
			}
			else if (0.4 < xcr && xcr <= 0.5)
			{
				return 0.42;
			}
			else if (0.3 < xcr && xcr <= 0.4)
			{
				return 0.32;
			}
			else return 0;
		}
		else if (100 < xht && xht <= 125)
		{
			if (xcr > 0.8)
			{
				return 0.61;
			}
			else if (0.7 < xcr && xcr <= 0.8)
```

```
		{
			return 0.48;
		}
		else if (0.6 < xcr && xcr <= 0.7)
		{
			return 0.38;
		}
		else if (0.5 < xcr && xcr <= 0.6)
		{
			return 0.33;
		}
		else if (0.4 < xcr && xcr <= 0.5)
		{
			return 0.14;
		}
		else return 0;
	}
	else if (125 < xht && xht <= 150)
	{
		if (xcr > 0.8)
		{
			return 0.41;
		}
		else if (0.7 < xcr && xcr <= 0.8)
		{
			return 0.35;
		}
		else if (0.6 < xcr && xcr <= 0.7)
		{
			return 0.32;
		}
		else if (0.5 < xcr && xcr <= 0.6)
		{
			return 0.13;
		}
		else return 0;
	}
	else if (150 < xht && xht <= 175)
	{
		if (xcr > 0.8)
		{
			return 0.35;
		}
		else if (0.7 < xcr && xcr <= 0.8)
		{
			return 0.32;
		}
		else if (0.6 < xcr && xcr <= 0.7)
		{
			return 0.21;
		}
		else return 0;
	}
	else
	{
		if (xcr > 0.8)
		{
			return 0.33;
```

```
                    }
                    else if (0.7 < xcr && xcr <= 0.8)
                    {
                           return 0.28;
                    }
                    else return 0;
             }
      }
      else return 0.98;
}

double ftl3 (double xht, double xcr)
{
      if (xht > 0 && xcr > 0)
      {
             return 0;
      }
}

double ftu1 (double xht, double xcr)
{
      if (xht > 0 && xcr > 0)
      {
             return 0;
      }
}

double ftu5 (double xht, double xcr)
{
      if (xht > 100)
      {
             if (xht <= 125)
             {
                    if (xcr > 0.8)
                    {
                           return 0.95;
                    }
                    else if (0.7 < xcr && xcr <= 0.8)
                    {
                           return 0.93;
                    }
                    else if (0.6 < xcr && xcr <= 0.7)
                    {
                           return 0.89;
                    }
                    else if (0.5 < xcr && xcr <= 0.6)
                    {
                           return 0.82;
                    }
                    else if (0.4 < xcr && xcr <= 0.5)
                    {
                           return 0.64;
                    }
                    else if (0.3 < xcr && xcr <= 0.4)
                    {
                           return 0.39;
                    }
                    else return 0.20;
```

```
}
else if (125 < xht && xht <= 150)
{
        if (xcr > 0.8)
        {
                return 0.78;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.67;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.52;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
                return 0.38;
        }
        else if (0.4 < xcr && xcr <= 0.5)
        {
                return 0.32;
        }
        else return 0;
}
else if (150 < xht && xht <= 175)
{
        if (xcr > 0.8)
        {
                return 0.55;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.43;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.35;
        }
        else if (0.5 < xcr && xcr <= 0.6)
        {
                return 0.31;
        }
        else return 0;
}
else
{
        if (xcr > 0.8)
        {
                return 0.41;
        }
        else if (0.7 < xcr && xcr <= 0.8)
        {
                return 0.35;
        }
        else if (0.6 < xcr && xcr <= 0.7)
        {
                return 0.32;
```

```
                        }
                        else if (0.5 < xcr && xcr <= 0.6)
                        {
                                return 0.14;
                        }
                        else return 0;
                }
        }
        else return 0.98;
}

double fsh4area (double xroad_loc, double xstand_dtr)
{
        if (xroad_loc == 0)
        {
                if (xstand_dtr == 0)
                {
                        return 201.1;
                }
                else if (xstand_dtr == 1)
                {
                        return 113.1;
                }
                else if (xstand_dtr == 2)
                {
                        return 50.3;
                }
                else if (xstand_dtr == 3)
                {
                        return 12.6;
                }
        }
        else if (xroad_loc == 1)
        {
                if (xstand_dtr == 1)
                {
                        return 12.6;
                }
                else if (xstand_dtr == 2)
                {
                        return 50.3;
                }
                else if (xstand_dtr == 3)
                {
                        return 113.1;
                }
                else if (xstand_dtr == 4)
                {
                        return 201.1;
                }
        }
}

double fsh5area (double xroad_loc, double xstand_dtr)
{
        if (xroad_loc == 0)
        {
                if (xstand_dtr == 0)
```

```
                {
                        return 201.1;
                }
                else if (xstand_dtr == 1)
                {
                        return 113.1;
                }
                else if (xstand_dtr == 2)
                {
                        return 50.3;
                }
                else if (xstand_dtr == 3)
                {
                        return 12.6;
                }
        }
        else if (xroad_loc == 1)
        {
                if (xstand_dtr == 1)
                {
                        return 12.6;
                }
                else if (xstand_dtr == 2)
                {
                        return 50.3;
                }
                else if (xstand_dtr == 3)
                {
                        return 113.1;
                }
                else if (xstand_dtr == 4)
                {
                        return 201.1;
                }
        }
}

double fsh6area (double xroad_loc, double xstand_dtr)
{
        if (xroad_loc == 0)
        {
                if (xstand_dtr == 0)
                {
                        return 201.1;
                }
                else if (xstand_dtr == 1)
                {
                        return 113.1;
                }
                else if (xstand_dtr == 2)
                {
                        return 50.3;
                }
                else if (xstand_dtr == 3)
                {
                        return 12.6;
                }
        }
```

```
	else if (xroad_loc == 1)
	{
		if (xstand_dtr == 1)
		{
			return 12.6;
		}
		else if (xstand_dtr == 2)
		{
			return 50.3;
		}
		else if (xstand_dtr == 3)
		{
			return 113.1;
		}
		else if (xstand_dtr == 4)
		{
			return 201.1;
		}
	}
}

double fsb1area (double xroad_loc, double xstand_dtr)
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 43.5;
		}
		else if (xstand_dtr == 1)
		{
			return 52.9;
		}
		else if (xstand_dtr == 2)
		{
			return 50.3;
		}
		else if (xstand_dtr == 3)
		{
			return 12.6;
		}
	}
	else if (xroad_loc == 1)
	{
		if (xstand_dtr == 1)
		{
			return 12.6;
		}
		else if (xstand_dtr == 2)
		{
			return 36.5;
		}
		else if (xstand_dtr == 3)
		{
			return 43.8;
		}
		else if (xstand_dtr == 4)
		{
```

```
				return 51.9;
			}
		}
	}

	double fsb2area (double xroad_loc, double xstand_dtr)
	{
		if (xroad_loc == 0)
		{
			if (xstand_dtr == 0)
			{
				return 201.1;
			}
			else if (xstand_dtr == 1)
			{
				return 113.1;
			}
			else if (xstand_dtr == 2)
			{
				return 50.3;
			}
			else if (xstand_dtr == 3)
			{
				return 12.6;
			}
		}
		else if (xroad_loc == 1)
		{
			if (xstand_dtr == 1)
			{
				return 12.6;
			}
			else if (xstand_dtr == 2)
			{
				return 50.3;
			}
			else if (xstand_dtr == 3)
			{
				return 113.1;
			}
			else if (xstand_dtr == 4)
			{
				return 201.1;
			}
		}
	}

	double ftl3area (double xroad_loc, double xstand_dtr)
	{
		if (xroad_loc == 0)
		{
			if (xstand_dtr == 0)
			{
				return 1.4;
			}
			else if (xstand_dtr == 1)
			{
				return 1.8;
```

```
                }
                else if (xstand_dtr == 2)
                {
                        return 2.3;
                }
                else if (xstand_dtr == 3)
                {
                        return 2.8;
                }
        }
        else if (xroad_loc == 1)
        {
                if (xstand_dtr == 1)
                {
                        return 1.2;
                }
                else if (xstand_dtr == 2)
                {
                        return 1.6;
                }
                else if (xstand_dtr == 3)
                {
                        return 2.0;
                }
                else if (xstand_dtr == 4)
                {
                        return 2.4;
                }
        }
}

double ftu1area (double xroad_loc, double xstand_dtr)
{
        if (xroad_loc == 0)
        {
                if (xstand_dtr == 0)
                {
                        return 6.3;
                }
                else if (xstand_dtr == 1)
                {
                        return 8.1;
                }
                else if (xstand_dtr == 2)
                {
                        return 10.0;
                }
                else if (xstand_dtr == 3)
                {
                        return 12.0;
                }
        }
        else if (xroad_loc == 1)
        {
                if (xstand_dtr == 1)
                {
                        return 6.1;
                }
```

```
		else if (xstand_dtr == 2)
		{
			return 7.5;
		}
		else if (xstand_dtr == 3)
		{
			return 9.0;
		}
		else if (xstand_dtr == 4)
		{
			return 10.7;
		}
	}
}

double ftu5area (double xroad_loc, double xstand_dtr)
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 129.0;
		}
		else if (xstand_dtr == 1)
		{
			return 113.1;
		}
		else if (xstand_dtr == 2)
		{
			return 50.3;
		}
		else if (xstand_dtr == 3)
		{
			return 12.6;
		}
	}
	else if (xroad_loc == 1)
	{
		if (xstand_dtr == 1)
		{
			return 12.6;
		}
		else if (xstand_dtr == 2)
		{
			return 50.3;
		}
		else if (xstand_dtr == 3)
		{
			return 113.1;
		}
		else if (xstand_dtr == 4)
		{
			return 149.9;
		}
	}
}

double fsh4cost (double xroad_loc, double xstand_dtr)
```

```
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 3800;
		}
		else if (xstand_dtr == 1)
		{
			return 3800;
		}
		else if (xstand_dtr == 2)
		{
			return 3800;
		}
		else if (xstand_dtr == 3)
		{
			return 3800;
		}
	}
	else if (xroad_loc == 1)
	{
		if (xstand_dtr == 1)
		{
			return 4262;
		}
		else if (xstand_dtr == 2)
		{
			return 4262;
		}
		else if (xstand_dtr == 3)
		{
			return 4262;
		}
		else if (xstand_dtr == 4)
		{
			return 4262;
		}
	}
}

double fsh5cost (double xroad_loc, double xstand_dtr)
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 3800;
		}
		else if (xstand_dtr == 1)
		{
			return 3800;
		}
		else if (xstand_dtr == 2)
		{
			return 3800;
		}
		else if (xstand_dtr == 3)
```

```
                {
                        return 3800;
                }
        }
        else if (xroad_loc == 1)
        {
                if (xstand_dtr == 1)
                {
                        return 4262;
                }
                else if (xstand_dtr == 2)
                {
                        return 4262;
                }
                else if (xstand_dtr == 3)
                {
                        return 4262;
                }
                else if (xstand_dtr == 4)
                {
                        return 4762;
                }
        }
}

double fsh6cost (double xroad_loc, double xstand_dtr)
{
        if (xroad_loc == 0)
        {
                if (xstand_dtr == 0)
                {
                        return 3800;
                }
                else if (xstand_dtr == 1)
                {
                        return 3800;
                }
                else if (xstand_dtr == 2)
                {
                        return 3800;
                }
                else if (xstand_dtr == 3)
                {
                        return 3800;
                }
        }
        else if (xroad_loc == 1)
        {
                if (xstand_dtr == 1)
                {
                        return 3800;
                }
                else if (xstand_dtr == 2)
                {
                        return 3800;
                }
                else if (xstand_dtr == 3)
                {
```

```
			return 3800;
		}
		else if (xstand_dtr == 4)
		{
			return 3800;
		}
	}
}

double fsb1cost (double xroad_loc, double xstand_dtr)
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 5036;
		}
		else if (xstand_dtr == 1)
		{
			return 5140;
		}
		else if (xstand_dtr == 2)
		{
			return 4565;
		}
		else if (xstand_dtr == 3)
		{
			return 3800;
		}
	}
	else if (xroad_loc == 1)
	{
		if (xstand_dtr == 1)
		{
			return 3815;
		}
		else if (xstand_dtr == 2)
		{
			return 4889;
		}
		else if (xstand_dtr == 3)
		{
			return 4973;
		}
		else if (xstand_dtr == 4)
		{
			return 5057;
		}
	}
}

double fsb2cost (double xroad_loc, double xstand_dtr)
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 4424;
```

```
			}
			else if (xstand_dtr == 1)
			{
				return 3883;
			}
			else if (xstand_dtr == 2)
			{
				return 3800;
			}
			else if (xstand_dtr == 3)
			{
				return 3800;
			}
		}
		else if (xroad_loc == 1)
		{
			if (xstand_dtr == 1)
			{
				return 3800;
			}
			else if (xstand_dtr == 2)
			{
				return 3800;
			}
			else if (xstand_dtr == 3)
			{
				return 2806;
			}
			else if (xstand_dtr == 4)
			{
				return 3890;
			}
		}
	}

	double ftl3cost (double xroad_loc, double xstand_dtr)
	{
		if (xroad_loc == 0)
		{
			if (xstand_dtr == 0)
			{
				return 1920;
			}
			else if (xstand_dtr == 1)
			{
				return 1951;
			}
			else if (xstand_dtr == 2)
			{
				return 3283;
			}
			else if (xstand_dtr == 3)
			{
				return 3316;
			}
		}
		else if (xroad_loc == 1)
		{
```

```
            if (xstand_dtr == 1)
            {
                  return 1887;
            }
            else if (xstand_dtr == 2)
            {
                  return 1914;
            }
            else if (xstand_dtr == 3)
            {
                  return 1941;
            }
            else if (xstand_dtr == 4)
            {
                  return 1968;
            }
      }
}

double ftu1cost (double xroad_loc, double xstand_dtr)
{
      if (xroad_loc == 0)
      {
            if (xstand_dtr == 0)
            {
                  return 3498;
            }
            else if (xstand_dtr == 1)
            {
                  return 3565;
            }
            else if (xstand_dtr == 2)
            {
                  return 3923;
            }
            else if (xstand_dtr == 3)
            {
                  return 3978;
            }
      }
      else if (xroad_loc == 1)
      {
            if (xstand_dtr == 1)
            {
                  return 3515;
            }
            else if (xstand_dtr == 2)
            {
                  return 3566;
            }
            else if (xstand_dtr == 3)
            {
                  return 3913;
            }
            else if (xstand_dtr == 4)
            {
                  return 3958;
            }
```

```
	}
}

double ftu5cost (double xroad_loc, double xstand_dtr)
{
	if (xroad_loc == 0)
	{
		if (xstand_dtr == 0)
		{
			return 5861;
		}
		else if (xstand_dtr == 1)
		{
			return 4803;
		}
		else if (xstand_dtr == 2)
		{
			return 3883;
		}
		else if (xstand_dtr == 3)
		{
			return 3800;
		}
	}
	else if (xroad_loc == 1)
	{
		if (xstand_dtr == 1)
		{
			return 3873;
		}
		else if (xstand_dtr == 2)
		{
			return 3883;
		}
		else if (xstand_dtr == 3)
		{
			return 4804;
		}
		else if (xstand_dtr == 4)
		{
			return 5957;
		}
	}
}

double fire_prob (double xmFRI, int xstage_length)
{
	return (exp (-(1 / xmFRI) * xstage_length)) * ((1 / xmFRI) *
		xstage_length);
}

double obj_funk (double xbio, double xCf, int xDhorizon, double xUr,
	double xnUr, double xUSTd, double xPd, double xCWDd, double xCp)
{
	return (xbio * xCf * ((xUr * xUSTd) * (1 - xPd * xDhorizon) +
		xnUr * (1 - xCWDd * xDhorizon) + xUr * (1 - xUSTd))) +
		xCp;
}
```