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ABSTRACT

The U.S.D.I. Office of Surface Mining (OSM) estimates that there are approximately 1 million acres of abandoned mine land (AML) in the Appalachian region. AML lands are classified as areas that were inadequately reclaimed or were left unreclaimed prior to the passage of the 1977 Surface Mining Control and Reclamation Act, and where no federal or state laws require any further reclamation responsibility to any company or individual. Reclamation and afforestation of these sites have the potential to provide landowners with cyclical timber revenues, generate environmental benefits to surrounding communities, and sequester carbon in the terrestrial ecosystem. Through a memorandum of understanding, the OSM and the U.S. Department of Energy (DOE) have decided to investigate reclaiming and afforesting these lands for the purpose of mitigating the negative effects of anthropogenic carbon dioxide in the atmosphere. This study determined the carbon sequestration potential of northern red oak (*Quercus rubra L.*), one of the major reclamation as well as commercial species, planted on West Virginia AML sites. Analyses were conducted to 1) calculate the total number of tons that can be stored, 2) determine the cost per ton to store carbon, and 3) calculate the profitability of managing these forests for timber production alone and for timber production and carbon storage together. The Forest Management Optimizer (FORMOP) was used to simulate growth data on diameter, height, and volume for northern red oak. Variables used in this study included site indicies ranging from 40 to 80 (base age 50), thinning frequencies of 0, 1, and 2, thinning percentages of 20, 25, 30, 35, and 40, and a maximum rotation length of 100 years. Real alternative rates of return (ARR) ranging from 0.5% to 12.5% were chosen for the economic analyses. A total of 769,248 thinning and harvesting combinations, net present worths, and soil expectation values were calculated in this study. Results indicate that the cost per ton to sequester carbon ranges from $6.54 on site index 80 land at a 12.5% ARR to $36.68 on site index 40 land at an ARR of 0.5%. Results also indicate that the amount of carbon stored during one rotation ranges between 38 tons per acre on site index 40 land to 58 tons per acre on site index 80 land. The profitability of afforestation on these AML sites in West Virginia increases as the market price for carbon increases from $0 to $100 per ton.

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# INTRODUCTION

Since the beginning of the Industrial Revolution, atmospheric concentration of carbon dioxide has risen about 30% resulting mainly from the combustion of fossil fuels (EPA 2002). The United States alone emits 1.2 gigatonnes of carbon to the atmosphere per year through fossil fuel combustion (24% of the world's total fossil fuel emissions) (Uzawa 1991). If this greenhouse gas addition is not stopped or at least slowed, the repercussions could be significant. By 2100, global average surface temperatures are expected to increase 1.4 to 5.8°C, global average water vapor concentration and precipitation is expected to increase, Northern Hemisphere snow and ice cover are expected to decrease further, and the global mean sea level is expected to rise 0.09 to 0.88 meters (IPCCa 2001). The Kyoto Protocol, an international accord, addresses this concern. Under this accord, the U.S. would have to reduce its carbon dioxide and other greenhouse gas emissions 7% below their 1990 levels by 2012 (Fletcher 2000). However, if the U.S. had signed the Kyoto Protocol the nation's economy could have been adversely affected. Most economic models suggest a 1% to 2% reduction in U.S. GDP as a result of Kyoto without emissions trading (IPCCb 2001). A U.S. Department of Energy model suggests that this reduction in GDP could have been as great as 4%, transforming the U.S.

economy from growth to recession, with potential significant repercussions on the global economy (EIA 1998). Therefore, new ideas to reduce greenhouse gases have been called for.

Forests cover about 746 million acres in the U.S. (USDA-FS 2001). These forests have the ability to sequester carbon at a rate of about 1 to 3 gigatonnes of carbon per year into their trees, understory vegetation, litter, and soils (Dixon et al. 1994). Improved forest management practices and afforestation of previously cleared forestland have resulted in a net uptake (sequestration) of carbon. This potential net uptake has resulted in forests being recognized as a potential carbon sink.

Forests of the Appalachian coal region present themselves as a possible opportunity to sequester large amounts of carbon. This 89 million acre region of the U.S. extends from Pennsylvania to Alabama and is approximately 12% of the total U.S. forest cover (Smith 1995). Within this region, there are officially 367,000 acres of abandoned mine land (AML) on record (USDI-OSM 2000) (Figure 1). However, the U.S.D.I. Office of Surface Mining (OSM) believes that this official 367,000 acres significantly underestimates the actual number of acres in AML land, which should be closer to 1 million acres. AML lands are classified as areas that were inadequately reclaimed or where left unreclaimed prior to the passage of the 1977 Surface Mining Control and Reclamation Act and where no federal or state laws require any further reclamation responsibility to any company or individual (USDI-OSM 2002). These areas contain little or no

INSERT FIGURE 1

vegetation, provide little wildlife habitat, and in some cases pollute streams. In an effort to repair these problem areas, reclamation and afforestation present a viable option. Reclamation and afforestation of these sites have the potential to sequester large amounts of carbon in the terrestrial ecosystems. Generally, afforestation represents one of the most cost-effective ways of reducing atmospheric carbon dioxide.

Combustion of fossil fuels by utility companies is one of the largest contributors to the rise in atmospheric carbon dioxide. Utility companies with high carbon dioxide emissions are interested in mitigating their emissions through the use of a carbon credit market where they can buy and sell carbon credits. In order to establish this carbon credit market, utility companies need to partner with landowners that had no forests prior to the partnership on their land in order to claim the carbon credits stored. AML sites in Appalachia may be an excellent location for utility companies to be paired with landowners because these lands (approximately 40% in private ownership (USDI-OSM 2001)) have no forests and provide no positive economic contribution.

Of the states in the Appalachian coal region, West Virginia has approximately one-quarter of the region's AML lands (USDI-OSM 2001). Therefore, this study examined the amount and cost of carbon that could be sequestered as well as the profitability of timber management with and without carbon credits for AML sites in West Virginia when planted with northern red oak

(*Quercus rubra L.*), one of the major commercial tree and reclamation species within this region.

## OBJECTIVES

The objectives of this study were:

1) To determine the profitability of forest management, when only timber is considered, in Northern red oak forests on abandoned mine lands in West Virginia.

2) To determine the financially optimal forest rotation schedule in Northern red oak forests on abandoned mine lands in West Virginia.

3) To determine the amount of carbon that can be stored in Northern red oak forests on abandoned mine lands in West Virginia.

4) To determine the profitability of forest management when both timber and carbon credits are considered in Northern red oak forests on abandoned mine lands in West Virginia.

5) To calculate the per ton cost of sequestering carbon in Northern red oak forests on abandoned mine lands in West Virginia.

6) To calculate the net revenue (or cost) for every ton of carbon stored in Northern red oak forests on abandoned mine lands in West Virginia.

# LITERATURE REVIEW

## Global Warming and Carbon Dioxide

The global climate is expected to change because anthropogenic activities, most notably the combustion of fossil fuels, are altering the Earth's atmospheric gas composition. Increasing concentrations of the "so-called" greenhouse gases is the area of greatest concern (Speth 1990). These gases, however, do occur naturally in our environment. They allow for the trapping of solar long wavelength radiation, which helps to maintain a temperature level that is suitable for sustaining life (Kimmins 1997). However, increasing gases may cause a rise in global temperature making changes to the narrow range of comfort in which today's societies have evolved (Trexler 1990).

During the 20$^{th}$ century, global average surface temperature has risen 0.6°C, and is expected to increase another 1.4 to 5.8°C by the end of the 21$^{st}$ century. Global average water vapor concentration and precipitation is expected to also increase. Northern Hemisphere snow and ice cover have decreased about 10% and are expected to decrease further. Global mean sea level has risen 0.1 to 0.2 meters and is expected to rise another 0.09 to 0.88 meters (IPCCa 2001).

Atmospheric carbon dioxide ($CO_2$) (the greenhouse gas of greatest concern) concentration is expected to double current levels by the middle of the 21st century (Sedjo 1989). This rise has mostly been attributed to the combustion of fossil fuels, but land-use changes, such as tropical forest depletion, have also been a major factor. Since the beginning of the Industrial Revolution, fossil fuel emissions have increased atmospheric $CO_2$ levels from 280 parts per million (ppm) to 367 ppm where currently 5.5 gigatonnes of carbon (GtC) are released annually. Land-use changes in terms of tropical forest depletion have increased $CO_2$ levels from 35 to 60 ppm where currently 1.6 GtC are released annually (IPCCa 2001). Though the true effects of $CO_2$ levels on the global climate are uncertain, it is a scientific consensus that the doubling of atmospheric carbon will have "serious environmental consequences" (US-DOE 1999).

## Forests and Carbon Storage

The sequestration potential of forests and the possibility of them acting as mitigating agents to carbon emissions, has become a major topic of discussion. Currently, forests store a total of 1,146 GtC of which 359 GtC is in above- and below-ground biomass and 787 GtC is stored in the forest soils. Annually, forests have the potential to sequester about 1 to 3 GtC (Dixon et al. 1994). These potentials have allowed the U.S. Department of Energy (DOE) to recognize forests as viable bodies of carbon storage in an effort to achieve net total sequestration rates of 1 GtC per year in 2025 and 4 GtC per year in 2050 (US-DOE 1999). With the potential of forests acting as carbon sequestration agents, it is important to understand how these sequestration rates are affected by different regional forest management practices (Sharpe and Johnson 1981).

Brown et al. (1996) noted three categories in which forest management practices (including managing for forest vegetation and soils) can be grouped in order to reduce $CO_2$ emission into the atmosphere: (1) management for carbon conservation, (2) management for carbon storage, and (3) management for carbon substitution. Management for carbon conservation is management through conserving current carbon pools by slowing the rate of loss and degradation of existing forest vegetation and soils. This can be achieved by controlling deforestation, protecting forests in reserves, changing harvesting regimes, and controlling other disturbances such as fire and pest outbreaks. Management for carbon storage (a more short-term option) is a technique that attempts to expand the amount of carbon stored in forest ecosystems by (1) increasing the total biomass and/or area and (2) increasing the amount of soil carbon density of natural and plantation forests. Management for carbon storage also attempts to increase storage in durable wood products. This type of management can be obtained by allowing carbon to be sequestered through natural or artificial regeneration, and by the enrichment of soil carbon on secondary and degraded forests whose maximum biomass and soil carbon storage have not been achieved. The third method, substitution management, has the greatest mitigation potential for the long-term. This method focuses more on the transfer of biomass carbon into products that substitute for, or lessen the use of, fossil fuels. Substitution management is gained by establishing new forests or plantations and/or increasing growth through different silvicultural techniques in hopes of increasing the use of wood products and fuels. Using these different forest management approaches, it has been estimated that 52 to 104 GtC could be sequestered over a fifty-year period in the entire world with a cost range of $247 billion to $302 billion (Brown et al. 1996).

Cannell (1996) poses four considerations that should be taken into account when managing forests for the maximization of carbon storage:

- Conserving native forests or replacing them with plantations
- Choosing the proper species and forest type
- The intensity and frequency of operations
- The conservation of soil carbon

Cannell states that native or unmanaged forests will normally contain a larger biomass (over a large area, or over a long period of time) than that of the typical plantation with similar growth rates and characteristics of the native forest. This occurs because the average age of a plantation is typically less than that of unmanaged forests and there is less detrital biomass. As a result, when native forests are clearcut and replaced with plantations, there is a net loss of carbon. This loss can be offset by intensively managing forests with fast growing tree species, and converting the harvested wood into long lasting wood products.

The choice of species and forest type must also be considered when managing for maximum carbon storage. When managing forests to store carbon over the short term, it is best to plant species that are faster growing because of their ability to sequester more carbon over the period of a few decades. When the carbon storage goal is more of a long term one, it is best to plant slow-growing species because of their ability to store more biomass until the time of harvest. The duration of carbon storage is directly affected by the management goal (Cannell 1996).

Cannell also points out that the intensity and frequency of operations play a vital role in maximizing carbon storage. At the time of harvest, the carbon in the living trees is transferred to the wood products. In the case of wood products with short rotations (i.e. pulpwood), even though mean annual yield is decreased, it is better to delay harvesting for as long as possible in an effort to store the largest amount of carbon possible. In the case of longer-lasting wood products with longer times until harvest, it is best to allow the growth of the forest to continue; thus, transferring more carbon to the product carbon pools. Cannell concludes that when forest management objectives produce wood products that are more long-lasting, the maximization of carbon storage and wood yield coincide (Cannell 1996).

The effects of forest management on soils must be thoroughly considered since soil carbon pools normally exceed that of the trees on the same site. When harvesting and site preparation operations occur, one might think that soil organic matter decomposition would increase due to the great soil disturbance that takes place, but this is not totally true (Cannell 1996). A study conducted by Johnson (1992) found there was no general trend in the decrease of soil carbon due to forest management harvest and reestablishment techniques. Actually, some sites (those that were fertilized or had nitrogen fixing species added) showed an increase in soil carbon. On the other hand, when forests are converted to row-crop agriculture, a great deal of soil carbon is released back to the atmosphere and is slowly regained when row-crop agricultural lands are transferred back to grasslands or forests (Johnson 1992).

## Appalachia and Abandoned Mine Lands

The Appalachian coal region of the eastern U.S. extends from Pennsylvania to Alabama of which, according to the U.S.D.I. Office of Surface Mining (OSM), there are officially 367,000 acres of land classified as abandoned mine land (AML) (USDI-OSM 2000). However, the OSM believes that this official 367,000 acres significantly underestimates the actual number of acres in AML land, which should be closer to 1 million acres. AML lands are classified as areas that were inadequately reclaimed or were left unreclaimed prior to the passage of the 1977 Surface Mining Control and Reclamation Act (SMCRA) and where no federal or state laws require any further reclamation responsibility to any company or individual (USDI-OSM 2002). The coals within this region are of

Pennsylvanian age, and the coal-bearing rock types are mainly fine-grained siltstones and shales although limestone is present in western Pennsylvania and Ohio. Many of the coal-bearing strata in the Appalachian region contain varying amounts of pyrite ($FeS_2$) (Vogel 1981). When this pyrite, facilitated by sulfur oxidizing bacteria, comes in contact with oxygen and water, sulfuric acid is produced (Brady and Weil 1996). This reaction is of considerable significance because (1) highly acid mine spoils limiting vegetation growth can be formed, and (2) acid mine drainage polluting major stream systems are likely and do occur as a result of most AML sites. Strongly alkaline coal-bearing strata are found in few areas, but are of minor consequence (Vogel 1981).

## AML Limitations

When considering reclamation of any type, especially on AML sites, it is important to realize that every site is very specific as to its minesoil composition; therefore, any reclamation attempt will be specific to the site considered. The chemical, physical, and biological properties of minesoils are the three main properties that affect successful afforestation either individually or in some combination on any mined site.

### Chemical Properties

Soil pH, acid-induced toxicities, and nutrient deficiencies are chemical properties of minesoils that are of most concern in afforestation efforts. Soil pH is probably the most useful criterion for determining the capacity of a minesoil to support vegetation. Generally, minesoils in the eastern U.S. are mostly in the acid range (pH below 7.0). Trees tend to be more tolerant of lower pH levels than that of herbaceous vegetation though all tree species do not have the same optimum pH level. When establishing trees on acid soils, it is not always necessary to lime except in extremely acidic conditions (Vogel 1981). Liming as a standard practice for tree establishment should not occur, as it may induce ground cover growth causing seedling mortality and growth restriction (Plass and Powell 1988). If liming on any particular site is necessary, liming above a pH of 5.5 should be avoided (Daniels and Zipper 1997).

Acid-induced toxicities occur in part when elements such as aluminum, iron, manganese, copper, nickel, and zinc become more soluble as pH levels decrease below 5.5. When concentrations of these elements exceed certain levels, they become toxic to plants. The best way of correcting these toxicity levels is by increasing the pH level of the soil to 5.5 or above (Vogel 1981).

Nitrogen (N) and phosphorus (P) are often the most limiting nutrients in minesoils. Fertilizer use on the establishment of herbaceous species is highly recommended, but the use on newly planted tree seedlings is not very predictable (Vogel 1981). This is not to say that the use of fertilizer should not take place. In some cases, especially on extremely acidic or infertile minesoils, fertilization can be beneficial, but fertilization rates should be moderate as to control the size and density of herbaceous ground cover (Plass and Powell 1988).

Another method of increasing soil N is by interplanting N-fixing tree species such as black locust (*Robinia pseudoacacia*) or European black alder (*Alnus glutinosa*) with commercial tree species. N-fixing trees in themselves do not fix N, but do so through a symbiotic relationship with *Rhizobium* bacteria or *Frankia* actinomycetes. These microorganisms dwell in root nodules and fix N in a usable form by trees, and in some cases, growth is enhanced in neighboring trees. Black locust, for example, when interplanted with pine has not been successful in promoting pine growth, but when planted with hardwoods some enhancement in growth has occurred (Ashby et al. 1985). European black alder, on the other hand, has been known to accelerate height and diameter growth for both pines and hardwoods (Plass 1977).

Physical Properties

The physical properties affecting establishment are soil texture, bulk density of the soil, and the slope and aspect. Soil texture is the relative proportion of sand, silt, clay, and coarse fragments. It affects drainage and water-holding capacity, soil structure, bulk density, erodibility, and cation exchange capacity. Minesoils often contain coarse rock fragments and tend to dry out quickly especially at the surface where seedling establishment is most critical. With a large proportion of fine particles such as clay, the surface can be plastic when wet, and hard when dry. Minesoils, with no adverse chemical compositions, are most suited to vegetation establishment with near-equal proportions of fine and coarse materials (Vogel 1981).

Bulk density is the weight of a unit volume of dry soil. Soils that are loose and porous have a low bulk density, and those soils that are highly compacted have a high bulk density. The size and volume of pores are important to the establishment of trees because they influence the movement and flow of water through the soil. High bulk densities (soils with less pore space) on today's mined sites is a major problem due to the extensive grading that has to take place in order to comply with SMCRA regulations. However, on AML sites, high bulk densities are not as much of a problem because heavy grading on a majority of these sites never took place. If an AML site is in need of grading, it should be done with caution because most of these sites have already begun the weathering and leaching process, and it could cause the underlying more acidic and toxic spoils to come to the surface (Vogel 1981).

The slope and aspect of a site should also be of consideration. The direction a slope is facing can affect the establishment of different tree species. South and west facing slopes tend to be hotter and drier than north and east facing slopes, therefore species planted on these sites should be more tolerant of these conditions. Most pine species tend to thrive better on the south and west facing slopes than most hardwood species (Burger and Torbert 1999).

Biological Properties

Microorganisms such as bacteria, fungi, and actinomycetes are in small numbers in minesoils as compared to normal forest soils. Organisms such as the *Rhizobium* bacteria and mycorrhizal fungi are very important to tree establishment. *Rhizobium* bacteria, as mentioned before, forms a symbiotic relationship with leguminous plants and in turn fix N into a usable form (Vogel 1981). Mycorrhizal fungi penetrate plant root systems forming a network that increases the plants effective root surface area. These fungi, specifically ectomycorrhizae, can increase plant growth in nutrient deficient soils (Kimmins 1997). A study conducted by Schoenholtz and Burger (1984) on pine inoculation with the ectomycorrhizal fungi *Pisolithus tinctorius*, showed that the pines were more tolerant of acidic sites causing them to grow faster than uninoculated seedlings.

Soil fauna are practically absent on newly disturbed mine sites, and only small populations may be present on AML sites. Soil fauna such as earthworms, beetles, bugs, and similar soil-dwelling creatures are primarily responsible for altering and mixing organic matter into the soil. Repopulation of these fauna could take years because of their slow recolonization rates (Vogel 1981).

## Carbon Storage Potential on AML Sites

Once tree establishment has occurred, AML sites in Appalachia have the potential to sequester carbon in a relatively short period of time. Skousen et al. (1994) evaluated the natural revegetation of 15 AML sites from three different coal beds (Pittsburgh, Freeport, and Kittanning) in West Virginia. The ages of these 15 AML sites ranged from 13 to 35 years. The pH on these sites ranged from 3.3 to 6.9. This study showed that ten tree species were common on at least one site on all three coal beds. Of those, red maple (*Acer rubrum*), black birch (*Betula lenta*), tuliptree (*Liriodendron tulipifera*), bigtooth aspen (*Populus grandidentata*), black cherry (*Prunus serotina*), northern red oak, and black locust occurred on seven or more sites. No tree was common on all sites, but black cherry occurred on 14 of the sites. Total tree canopy cover was lowest on the Kittanning sites with an average of 33%. The highest total tree canopy cover was found on the Freeport sites having an average of 145% (due to different canopy layers). The sites with the lower total canopy cover generally had higher pH levels allowing for quicker herbaceous ground cover reducing tree establishment opportunity. The sites with lower pH levels had a higher tree canopy cover from seeding in by adjacent forests. This study showed that a forest could be established on unreclaimed minesoils when the conditions favor tree establishment.

Caldwell et al. (1992) conducted a study on an AML site in Perry County, Ohio with a pH of 2.8. This study evaluated the survival and growth of *Pisolithus tinctorius* inoculated Virginia and eastern white pines (*Pinus virginiana* and *Pinus strobus*, repectively) planted in March of 1986 with non-inoculated European black alder, black locust, silky dogwood (*Cornus amomum*), gray dogwood (*Cornus racemosa*), and tatarian honeysuckle (*Lonicrea tatarica*). The pines comprised 70% of the seedlings planted. By 1988, all of the silky dogwood, gray dogwood, and tatarian honeysuckle were dead, 100% of the pines remained, and 75% of the locust and alder remained. In 1988, a permanent plot was established to evaluate the survival and growth of the Virginia pine. This plot in 1992 showed that 98% of the pines remained with a mean basal diameter of 5.14 centimeters, and a mean height of 289.6 centimeters.

The potential of AML sites to sequester carbon can also be shown through pre-SMCRA forest establishment in the eastern U.S. Many of the early plantations on mined lands were established successfully with minimal pre-planting reclamation techniques, if any at all. Vogel (1977) discusses measurements taken in 1975 on 13 U.S.D.A. Forest Service plantations in southeastern Ohio planted in 1946 and 1947. It was shown that green ash (*Fraxinus pennsylvanica*) and white ash (*Fraxinus americana*) had the best survival (55 and 44%, respectively), but their growth (10.16 and 11.43 centimeters DBH and 8.2 and 10.1 meters in height, respectively) was poor in comparison to the other species. The best growth was shown in the eastern white pine and tuliptree (15.75 and 14.48 centimeters DBH and 9.1 and 11.0 meters in height, respectively). It was also stated that on most of the sites the combination of planted and natural vegetation was similar to adjacent unmined sites. Also discussed were measurements taken in 1976 on research plantings made by Pennsylvania State University in 1946 and 1947. This study showed that northern red oak and hybrid poplar (*Populus* sp.) had the best performance, 13.46 centimeters DBH and 11.3 meters in height and 22.86 centimeters DBH and 19.2 meters in height, respectively.

Davidson (1981) conducted a study to determine timber volumes of 19 Pennsylvania surface mine plantations established between 1919 and 1934. Volumes per acre of planted and volunteer species were determined along with soil development within the plantation. Jack pine (*Pinus banksiana*) yielded the highest volume, 10,567 International ¼-inch board feet per acre. Red pine (*Pinus resinosa*), included only in the younger plantations, had 7,364 International ¼-inch board feet per acre, and eastern white pine, Scots pine (*Pinus sylvestris*), and Norway spruce (*Picea abies*) yielded 4,284, 4,577, and 4,688 International ¼-inch board feet per acre, respectively. Volunteer species were black cherry, red maple, sugar maple (*Acer saccharum*), aspen (*Populus* sp.), and beech (*Fagus grandifolia*) yielding 1,606, 592, 327, 271, and 200 International ¼-inch board feet per acre, respectively. Examination of the soil profile showed definite soil horizon development. Davidson concluded that commercial harvests are possible on old-planted minesoils.

## Northern Red Oak

Northern red oak is a moderate to fast growing species found on a wide variety of soils and topography within the eastern U.S. (Sander 1990). This widespread tree species is highly valued for wildlife food and habitat, timber and veneer, aesthetics, and as an urban tree (Isebrands and Dickson 1994). Northern red oak is the only oak found extending south from Nova Scotia to southern Alabama, and east from eastern Nebraska to North Carolina. This species is found on all topographic positions, but grows best on middle to lower slopes with northerly to easterly aspects. It grows at elevations up to 3,500 ft in West Virginia and up to 5,500 ft in the southern Appalachians (Sander 1990). Stands dominated by northern red oak are typically of even-age with site indicies ranging from 50 to 110 (base age 50). Pure northern red oak stands are common in the transition zone between the oak-hickory and mixed mesophytic forests of the Central and Appalachian Harwood Regions, the southern Appalachians, the former and northern hardwood forests of the Lake States and New England, and the Driftless Area of southwestern Wisconsin (Johnson 1994).

Depending on management objectives, site quality, and other factors, rotation lengths for sawtimber range from 80 to 120 years. In southwestern Wisconsin, normal 100-year-old northern red oak stands can have a gross yield from 3,200 cubic feet per acre on site index 50 (base age 50) land to 6,200 cubic feet per acre on site index 70 (base age 50) land. Northern red oak in West Virginia can exceed diameter growth of other oaks within the same region (Johnson 1994).

# METHODS

This study was designed to determine the profitability of forest management with timber only and with timber and carbon credits, optimal thinning and harvesting schedules, the number of tons of carbon that can be sequestered, the cost of sequestration, and the net revenue (or cost) for every ton of stored carbon for northern red oak (*Quercus rubra L.*) on AML sites in the state of West Virginia. The Forest Management Optimizer (FORMOP) was used to simultaneously determine the financially optimal timing and intensity for thinning(s) and the financially optimal rotation age for northern red oak. FORMOP combines the Forest Vegetation Simulator (FVS), used to simulate stand growth data on diameter, height, and volume, for stands from establishment to final harvest, with an economic program to calculate cash flow tables, net present worths (NPW), and soil expectation values (SEV). A flow chart of the methodology can be found in Figure 2.

## 1. Obtain northern red oak growth and yield data

FORMOP was developed to simulate stand growth and yield data with and without thinnings and conduct economic analyses. Growth and yield data for

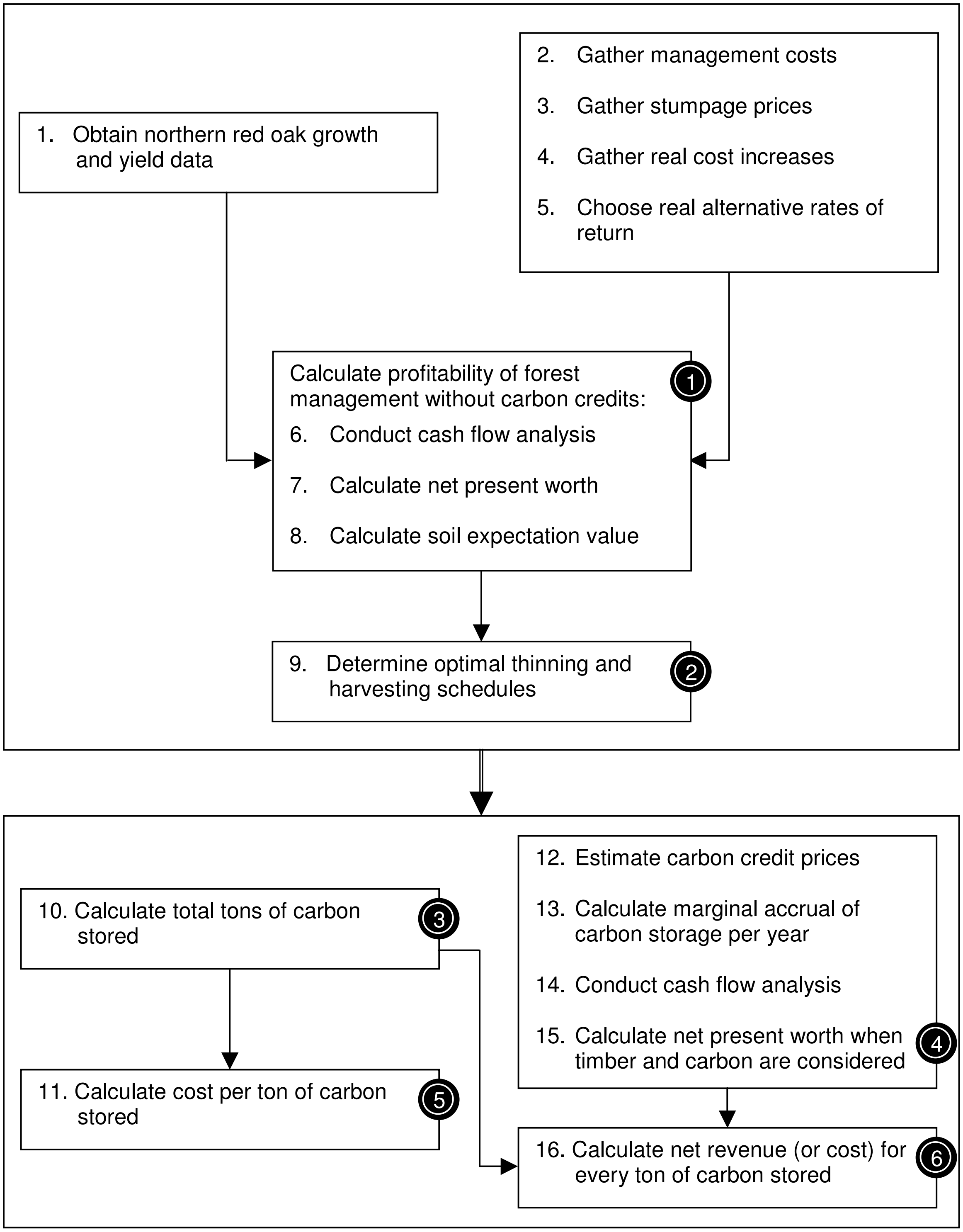


Figure 2. Flow chart of methodology; circled number denotes objective number completed.

northern red oak were obtained using FVS, a product of the U.S.D.A. Forest Service. FVS is an individual tree, distance-independent, growth and yield model. FVS contains modules that simulate tree growth, predict mortality, establish regeneration, perform management activities, calculate tree volumes, and produce reports on stand structure (Teck et al. 1996). A dynamic program (similar to a dynamic model developed by Huang (1999) for loblolly pine plantations in East Texas) was designed. FVS was linked within FORMOP through the use of a dynamic program that simultaneously determines the financially optimal timing and intensity for thinning(s) and the financially optimal rotation age for northern red oak through the maximization of the soil expectation value over the rotations.

Site indicies 40, 50, 60, 70, and 80 (base age 50) were used in this study. This range of site indicies best represents the productivity of current AML sites (Burger 2002). It was assumed that 500 trees per acre would be planted and 350 trees per acre would remain after 10 years. The maximum rotation length was set to 100 years where 0, 1, or 2 thinnings were possible. The first entry into the stand could not occur before age 20, and there had to be at least 10 years between any thinning or between any thinning and final harvest. Thinnings were conducted as a percent basal area removal from below where 20, 25, 30, 35, and 40% removals were considered.

Any thinning and final harvest schedule was considered operable only if two main constraints were met: 1) a minimum of 70 trees per acre were remaining after any thinning, and 2) a minimum of 6 cords or 1500 Doyle board feet were removed. The first constraint was set to reduce the effect of inadequate residual stand density. The second constraint was set to ensure that the amount of volume removed was saleable.

Sawlog requirements were set at a minimum DBH of 11 inches and a minimum top diameter of 9.6 inches inside bark. Pulpwood volume requirements were set at a minimum DBH of 6 inches and a minimum top diameter of 4 inches inside bark.

2. Gather management costs

Management costs are those costs associated with establishing, maintaining, and harvesting a stand of trees. All costs used were current market prices. For the purpose of this study, stand establishment requiring low and high site preparation costs were considered. It was also assumed that the environmental engineering problems sometimes associated with abandoned mine lands had been corrected, and these lands were ready for normal forestry practices. All assumed management costs and the timing of the costs are presented in Table 1.

Stand establishment costs used in this study included boundary location, an initial management plan, site preparation, and seedlings and planting. For both the low and high site preparation cost scenarios, boundary location was

Table 1. Summary of management activities, costs, and frequencies used.

| Activity | Cost[1] | Starting Year | Frequency |
|---|---|---|---|
| Boundary location | $20 | Year 0 | Only once |
| Boundary maintenance | $2 | Year 10 | Every 10 years |
| Management plan (initial) | $5 | Year 0 | Only once |
| Management plan (update) | $10 | Year 10 | Every 10 years |
| Site Preparation | | Year 0 | Only once |
| Ripping | $35 | | |
| Herbicide | $40 | | |
| Liming[2] | $225 | | |
| Hydroseeding and fertilization[2] | $800 | | |
| Seedlings and Planting | $225 | Year 0 | Only once |
| Mark and administer timber sale (percentage of gross) | 10% | As Needed | As Needed |

[1]All costs on a per acre basis.
[2]Used only with high site preparation cost scenario.

assumed to cost $20 per acre, the initial management plan was $5 per acre, and seedlings and planting were $225 per acre. The site preparation costs differed however between the low and high site preparation cost scenarios. Site preparation for the low site preparation cost scenario included ripping and herbicide at assumed costs of $35 and $40 per acre, respectively. The high site preparation cost scenario also included the costs for ripping and herbicide, but costs for liming and hydroseeding and fertilization also were included. Liming is used to correct for problems associated with high acidity. It was assumed that lime would be applied at a rate of 5 tons per acre at a cost of $45 per ton. Hydroseeding and fertilization is applied in a slurry mix containing grass seed, mulch, and fertilizer. This application is used to correct erosion problems. It was assumed that this slurry mix would be applied at the rate of 60 lbs per acre of grass seed, 1000 pounds per acre of mulch, and 400 pounds per acre of 15-30-15 fertilizer at a total cost of $800 per acre. All site preparation and seedlings and planting costs were assumed to occur only at the beginning of the first rotation.

Stand maintenance costs used in this study were for boundary and management plan updates. Boundary maintenance was assumed to cost $2 per acre and would begin in year 10, occurring every 10 years. Management plan updates are also necessary in order to account for stand changes occurring over time. Updates were assumed to cost $10 per acre and would also begin in year 10, occurring every 10 years.

When a stand is harvested, the timber to be removed must be marked for sale, and the sale must be administered. The marking and administration costs were assumed to be 10% of the gross timber sale receipts.

3. Gather stumpage prices

The stumpage prices used in this analysis came from current and historical stumpage data. The price for sawtimber was assumed to be $357 per thousand board feet (Doyle log rule), and pulpwood was $6.75 per cord (West Virginia Division of Forestry 1997-2001).

4. Gather real cost increases

The real cost increase for labor was assumed to be 1.12% (Council of Economic Advisors 2001). A real rate is one that has the effect of inflation removed.

5. Choose real alternative rates of return

An alternative rate of return (ARR) is an individual's opportunity cost of capital. This rate is chosen by obtaining an individual's best alternative use for his or her money. A specific landowner's ARR is difficult to determine.

Therefore, real ARRs of 0.5, 2.5, 5.0, 7.5, 10.0, and 12.5 percent were chosen for this study. These interest rates best reflect individuals with the following situations (Kronrad 2002):

1) A real interest rate of 0.5% is a rate that reflects short-term government bonds or bank CD's.
2) A real interest rate of 2.5% reflects the approximate return that may be earned on U.S. Treasury bonds.
3) A real interest rate of 5.0% approximates the return earned from high grade corporate bonds.
4) A real interest rate of 7.5% reflects the long-term average yielded from the U.S. stock market.
5) Real interest rates of 10.0 and 12.5 percent are rates that can be earned on investments such as real estate, private investments, and private businesses.

### 6. Conduct discounted cash flow analysis

Discounted cash flow analysis requires all expected inputs and outputs be specified quantitatively, each input and output be scheduled, a value be placed on each input and output, and these data must be combined into some measure of profitability (Gregory 1987). By using the previously mentioned costs, revenues, real cost increases, and real ARRs, a discounted value for each input and output was derived for each thinning and harvesting schedule evaluated.

7. Calculate net present worth

Net present worth (NPW) is the discounted or present value of the revenues minus the present value of the costs for a given ARR. The NPW shows the dollar amount that would be earned above the investor's ARR. For example, if an investor earned an NPW of $100 at an ARR of 10.5%, this investor would make $100 plus their ARR of 10.5%.

8. Calculate soil expectation value

Martin Faustmann (1849), a German forester, first introduced the soil expectation value (SEV), or land expectation value (LEV), to the forestry community. The SEV is the NPW of bare forestland for timber production over a perpetual series of rotations, and is commonly used to compare forest investments of different rotation lengths (Gregory 1987). The SEV formula is:

$$SEV = \left\{ \sum_{y=0}^{n} \left[ \frac{R_y}{(1+r)^y} - \frac{C_y}{(1+r)^y} \right] \right\} \left\{ \left[ \frac{1}{(1+r)^n - 1} \right] + 1 \right\}$$

where,

$R_y$ = revenue in year $y$

$C_y$ = cost in year $y$

$n$ = number of years in the rotation

$r$ = real discount rate, percent / 100

$y$ = year at which the revenue or cost occurs

9. Determine optimal thinning and harvesting schedules

The thinning and harvesting schedule that maximized SEV for a given site index / ARR combination was considered to be the optimal thinning and harvesting schedule. The optimal rotation setting for both the high and low site preparation cost scenarios for any given site index / ARR combination was the same because the site preparation costs were only applied at the beginning of the first rotation and did not affect the maximization decision.

10. Calculate total tons of carbon stored

Once the optimal thinning and harvesting schedules were determined, the total tons of carbon stored for each optimal rotation could be estimated. First, individual total tree biomass had to be determined. Total above-ground tree biomass was estimated using dry weight equations for northern red oak in the southern Appalachian mountains (Clark and Schroeder 1986). If an individual tree was less than 11 inches DBH, then the dry weight equation employed was:

$$Y = 0.15595(D^2 Th)^{0.93760}$$

where,

$Y$ = total-stem wood and bark, pounds

$D$ = DBH, inches

$Th$ = total tree height, feet.

If an individual tree was greater than or equal to 11 inches DBH, then the dry weight equation employed was:

$$Y = 0.14071(D^2)^{0.95903}(Th)^{0.93760}$$

where,

$Y$ = total-stem wood and bark, pounds

$D$ = DBH, inches

$Th$ = total tree height, feet.

In these equations, total-stem wood and bark weight includes all stem wood and stem bark and all branch wood and branch bark from the ground-line up. Below-ground biomass was assumed to be 15.5% of the total tree oven-dry weight of both the above- and below-ground tree portions, or a conversion factor from above-ground biomass to total tree biomass of 1.183 (Koch 1989). Carbon content of the total tree was assumed to be 50% of the oven-dry weight (Koch 1989). Pounds of carbon were then converted to tons of carbon (2000 pounds per ton). Once the carbon content of each individual tree was determined, tons of carbon stored per acre for standing trees could be determined. When harvesting operations took place (either thinnings or final harvest), it was assumed that all merchantable wood went into long-lived wood products and all non-merchantable wood was lost at the time of harvest. Finally, carbon stored in the soil and litter were estimated from Birdsey (1996). In the Mid-Atlantic region, soil carbon was estimated to be 24 tons per acre (the difference between forestland and grassland soil carbon), and litter was estimated to be 8 tons per acre. Once all inputs and outputs for the total carbon stored were determined, they were added to derive the total tons of carbon stored for each optimal rotation.

### 11. Calculate cost per ton of carbon stored

The cost per ton of carbon stored was calculated by dividing the total discounted costs (determined in the discounted cash flow analysis) by the total number of tons stored.

### 12. Assume carbon credit prices

In this study, one carbon credit was assumed to be one ton of stored carbon. Since there is no true carbon credit market in the U.S., prices per ton of carbon had to be assumed. Four carbon credit prices were assumed and used in the analysis. First, a value of $0 per ton was used in order to establish a baseline set of data assuming no carbon credit market. Values of $10, $50, and $100 per ton were used because they are prices most often discussed in the literature concerning a potential carbon credit market.

13. Calculate marginal accrual of carbon storage per year

It was assumed that utility companies would pay landowners for carbon stored on a yearly basis. Therefore, the amount of carbon stored during each year had to be determined. The marginal amount of carbon stored in any given year was determined in a manner similar to that of determining the total number of tons stored (step 10). The marginal amount of carbon stored in any given year was simply the total above- and below-ground carbon stored up to the year in question minus the total amount of carbon stored up to the previous year. Timber removals in any given year (minus the proportion that went into long-lived wood products) were considered a loss. It was possible to have a negative accumulation in any given year due to timber removals and/or mortality. Yearly accumulations of carbon from soil and litter were not considered in this portion of the analysis due to a lack of data on yearly accrual rates.

14. Conduct discounted cash flow analysis

Each year's marginal accrual was multiplied by the price of carbon in order to determine a carbon value in dollars for each year of the rotation. The present value for each year's carbon accrual value was then determined through discounted cash flow analysis.

15. Calculate net present worth when both timber and carbon are considered

A NPW for carbon only was then calculated. This NPW for carbon was added to the NPW for timber management only in order to obtain an NPW for both timber management and carbon credits.

16. Calculate net revenue (or cost) for every ton of carbon stored

The net revenue was calculated by dividing the NPW for both timber management and carbon credits by the total number of tons stored. This value shows the exact dollar value gained or lost per ton of carbon stored.

# RESULTS

A total of 769,158 thinning and harvesting combinations, NPWs, and SEVs were calculated. SEVs were calculated based on timber revenues and management costs under the scenario of timber management only. However, NPWs were calculated under two scenarios: timber management only and timber management plus carbon credits. For simplification, the NPWs from timber management only will be referred to as $NPW_T$, and the NPWs from timber management and carbon credits will be referred to as $NPW_{T+C}$.

The thinning and harvesting schedules that maximize the SEV for each site index / ARR combination are presented in Table 2. Tables 3 and 4 show the SEV values for the low and high site preparation cost scenarios, respectively. The NPWs for the rotations with the financially optimal thinning and harvesting schedules, using low and high site preparation costs, are presented in Tables 5 and 6, respectively. Table 7 shows the total number of tons stored per acre for the optimal rotations. The costs per ton are presented in Tables 8 and 9. Tables 10 through 19 show the NPW values when timber management and carbon credits are combined for low and high site preparation costs on AML sites. The net revenue (or cost) for every ton of carbon stored when timber management and carbon credits are combined is presented in Tables 20 through 29.

Table 2. Optimal rotation schedules that maximize soil expectation value for northern red oak planted on West Virginia abandoned mine lands.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | **100**[2] | **100** | **100** | **48** | **43** | **43** |
| 50 | 58[3]-**97** (40%)[4] | 58-**76** (40%) | 58-**76** (40%) | 58-**76** (40%) | **33** | **33** |
| 60 | 57-69-**98** (30%) | 57-68-**96** (30%) | 43-**63** (40%) | 43-**63** (40%) | **27** | **27** |
| 70 | 44-72-**99** (30%) | 44-58-**82** (30%) | 35-**55** (40%) | 35-**55** (40%) | 35-**55** (40%) | **25** |
| 80 | 31-**90** (40%) | 31-**70** (40%) | 31-**57** (40%) | 31-**49** (40%) | 31-**49** (40%) | 31-**49** (40%) |

[1]Base age 50.
[2]Bolded number indicates final harvest year.
[3]Number(s) indicates age(s) at thinning(s).
[4]Number in parenthesis indicates basal area removed during thinning(s).

Table 3. Soil expectation value, per acre, for northern red oak planted on West Virginia abandoned mine lands assuming low site preparation costs.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | $628.09 | ($308.55) | ($343.90) | ($337.65) | ($333.59) | ($331.12) |
| 50 | $1,530.08 | ($230.85) | ($327.68) | ($335.23) | ($332.79) | ($330.72) |
| 60 | $3,181.49 | ($112.78) | ($302.87) | ($328.13) | ($331.21) | ($329.83) |
| 70 | $4,654.70 | $23.12 | ($275.87) | ($318.65) | ($327.89) | ($328.65) |
| 80 | $5,511.72 | $159.88 | ($236.18) | ($305.75) | ($322.81) | ($327.26) |

[1]Base age 50.

Table 4. Soil expectation value, per acre, for northern red oak planted on West Virginia abandoned mine lands assuming high site preparation costs.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | ($396.91) | ($1,333.55) | ($1,368.90) | ($1,362.65) | ($1,358.59) | ($1,356.12) |
| 50 | $505.08 | ($1,255.85) | ($1,352.68) | ($1,360.23) | ($1,357.79) | ($1,355.72) |
| 60 | $2,156.49 | ($1,137.78) | ($1,327.87) | ($1,353.13) | ($1,356.21) | ($1,354.83) |
| 70 | $3,629.70 | ($1,001.88) | ($1,300.87) | ($1,343.65) | ($1,352.89) | ($1,353.65) |
| 80 | $4,486.72 | ($865.12) | ($1,261.18) | ($1,330.75) | ($1,347.81) | ($1,352.26) |

[1]Base age 50.

Table 5. Net present worth, per acre, for northern red oak planted on West Virginia abandoned mine lands assuming low site preparation costs.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | $67.28 | ($307.85) | ($343.59) | ($336.56) | ($333.08) | ($330.95) |
| 50 | $407.55 | ($241.18) | ($327.04) | ($335.09) | ($331.51) | ($330.16) |
| 60 | $1,056.66 | ($129.85) | ($302.74) | ($327.85) | ($329.05) | ($328.73) |
| 70 | $1,645.78 | ($18.50) | ($277.44) | ($318.32) | ($327.76) | ($327.31) |
| 80 | $1,820.30 | $80.22 | ($239.95) | ($305.59) | ($322.62) | ($327.18) |

[1]Base age 50.

Table 6. Net present worth, per acre, for northern red oak planted on West Virginia abandoned mine lands assuming high site preparation costs.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | ($957.72) | ($1,332.85) | ($1,368.59) | ($1,361.56) | ($1,358.08) | ($1,355.95) |
| 50 | ($617.45) | ($1,266.18) | ($1,352.04) | ($1,360.09) | ($1,356.51) | ($1,355.16) |
| 60 | $31.66 | ($1,154.85) | ($1,327.74) | ($1,352.85) | ($1,354.05) | ($1,353.73) |
| 70 | $620.78 | ($1,043.50) | ($1,302.44) | ($1,343.32) | ($1,352.76) | ($1,352.31) |
| 80 | $795.30 | ($944.78) | ($1,264.95) | ($1,330.59) | ($1,347.62) | ($1,352.18) |

[1]Base age 50.

Table 7. Total tons of carbon stored per acre for West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | 43 | 43 | 43 | 38 | 38 | 38 |
| 50 | 47 | 45 | 45 | 45 | 38 | 38 |
| 60 | 53 | 53 | 47 | 47 | 39 | 39 |
| 70 | 57 | 55 | 49 | 49 | 49 | 41 |
| 80 | 58 | 55 | 53 | 51 | 51 | 51 |

[1]Base age 50.

Table 8. Cost per ton of carbon stored when site preparation costs are low on West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | $12.94 | $9.15 | $8.14 | $8.83 | $8.90 | $8.83 |
| 50 | $12.16 | $8.65 | $7.79 | $7.52 | $8.72 | $8.66 |
| 60 | $12.21 | $7.83 | $7.52 | $7.24 | $8.56 | $8.51 |
| 70 | $12.35 | $7.69 | $7.29 | $6.99 | $6.87 | $8.17 |
| 80 | $12.52 | $7.70 | $6.82 | $6.74 | $6.61 | $6.54 |

[1]Base age 50.

Table 9. Cost per ton of carbon stored when site preparation costs are high on West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Site Index[1] | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| 40 | $36.68 | $32.90 | $31.89 | $35.59 | $36.23 | $36.16 |
| 50 | $33.97 | $31.34 | $30.49 | $30.21 | $35.52 | $35.46 |
| 60 | $31.64 | $27.35 | $29.33 | $29.04 | $34.93 | $34.88 |
| 70 | $30.19 | $19.12 | $28.32 | $28.03 | $27.90 | $33.47 |
| 80 | $30.12 | $26.20 | $26.28 | $26.96 | $26.83 | $26.77 |

[1]Base age 50.

Table 10. Net present worth per acre with timber management and carbon credits for low site preparation costs on site index 40 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $67.28 | ($307.85) | ($343.59) | ($336.56) | ($333.08) | ($330.95) |
| $10/ton | $178.74 | ($231.53) | ($302.14) | ($315.20) | ($318.84) | ($320.64) |
| $50/ton | $624.58 | $73.74 | ($136.35) | ($229.76) | ($261.86) | ($279.41) |
| $100/ton | $1,181.88 | $455.33 | $70.89 | ($122.96) | ($190.64) | ($227.87) |

Table 11. Net present worth per acre with timber management and carbon credits for high site preparation costs on site index 40 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | ($957.72) | ($1,332.85) | ($1,368.59) | ($1,361.56) | ($1,358.08) | ($1,355.95) |
| $10/ton | ($846.26) | ($1,256.53) | ($1,327.14) | ($1,340.20) | ($1,343.84) | ($1,345.64) |
| $50/ton | ($400.42) | ($951.26) | ($1,161.35) | ($1,254.76) | ($1,286.86) | ($1,304.41) |
| $100/ton | $156.88 | ($569.67) | ($954.11) | ($1,147.96) | ($1,215.64) | ($1,252.87) |

Table 12. Net present worth per acre with timber management and carbon credits for low site preparation costs on site index 50 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $407.55 | ($241.18) | ($327.04) | ($335.09) | ($331.51) | ($330.16) |
| $10/ton | $554.77 | ($145.28) | ($267.51) | ($297.36) | ($310.91) | ($314.61) |
| $50/ton | $1,143.64 | $238.30 | ($29.39) | ($146.46) | ($228.51) | ($252.40) |
| $100/ton | $1,879.72 | $717.77 | $268.26 | $42.17 | ($125.50) | ($174.64) |

Table 13. Net present worth per acre with timber management and carbon credits for high site preparation costs on site index 50 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | ($617.45) | ($1,266.18) | ($1,352.04) | ($1,360.09) | ($1,356.51) | ($1,355.16) |
| $10/ton | ($470.23) | ($1,170.28) | ($1,292.51) | ($1,322.36) | ($1,335.91) | ($1,339.61) |
| $50/ton | $118.64 | ($786.70) | ($1,054.39) | ($1,171.46) | ($1,253.51) | ($1,277.40) |
| $100/ton | $854.72 | ($307.23) | ($756.74) | ($982.83) | ($1,150.50) | ($1,199.64) |

Table 14. Net present worth per acre with timber management and carbon credits for low site preparation costs on site index 60 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $1,056.66 | ($129.85) | ($302.74) | ($327.85) | ($329.05) | ($328.73) |
| $10/ton | $1,257.32 | $11.13 | ($227.18) | ($277.52) | ($303.54) | ($308.88) |
| $50/ton | $2,059.98 | $575.03 | $75.08 | ($76.21) | ($201.48) | ($229.49) |
| $100/ton | $3,063.30 | $1,279.90 | $452.91 | $175.44 | ($73.90) | ($130.26) |

Table 15. Net present worth per acre with timber management and carbon credits for high site preparation costs on site index 60 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $31.66 | ($1,137.78) | ($1,327.74) | ($1,352.85) | ($1,354.05) | ($1,353.73) |
| $10/ton | $232.32 | ($996.80) | ($1,252.18) | ($1,302.52) | ($1,328.54) | ($1,333.88) |
| $50/ton | $1,034.98 | ($432.90) | ($949.92) | ($1,101.21) | ($1,226.48) | ($1,254.49) |
| $100/ton | $2,038.30 | $271.97 | ($572.09) | ($849.56) | ($1,098.90) | ($1,155.26) |

Table 16. Net present worth per acre with timber management and carbon credits for low site preparation costs on site index 70 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $1,645.78 | ($18.50) | ($277.44) | ($318.32) | ($327.76) | ($327.31) |
| $10/ton | $1,894.03 | $148.48 | ($182.47) | ($251.69) | ($280.13) | ($299.33) |
| $50/ton | $2,887.03 | $816.41 | $197.41 | $14.81 | ($89.61) | ($187.40) |
| $100/ton | $4,128.29 | $1,651.32 | $672.27 | $347.94 | $148.53 | ($47.49) |

Table 17. Net present worth per acre with timber management and carbon credits for high site preparation costs on site index 70 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $620.78 | ($1,043.50) | ($1,302.44) | ($1,343.32) | ($1,352.76) | ($1,352.31) |
| $10/ton | $869.03 | ($876.52) | ($1,207.47) | ($1,276.69) | ($1,305.13) | ($1,324.33) |
| $50/ton | $1,862.03 | ($208.59) | ($827.59) | ($1,010.19) | ($1,114.61) | ($1,212.40) |
| $100/ton | $3,103.29 | $626.32 | ($352.73) | ($677.06) | ($876.47) | ($1,072.49) |

Table 18. Net present worth per acre with timber management and carbon credits for low site preparation costs on site index 80 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $1,820.30 | $80.22 | ($239.95) | ($305.59) | ($322.62) | ($327.18) |
| $10/ton | $2,084.61 | $263.76 | ($123.17) | ($226.06) | ($264.75) | ($284.22) |
| $50/ton | $3,141.86 | $997.94 | $343.96 | $92.06 | ($33.26) | ($112.37) |
| $100/ton | $4,463.41 | $1,915.66 | $927.88 | $489.72 | $256.11 | $102.44 |

Table 19. Net present worth per acre with timber management and carbon credits for high site preparation costs on site index 80 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $795.30 | ($944.78) | ($1,264.95) | ($1,330.59) | ($1,347.62) | ($1,352.18) |
| $10/ton | $1,059.61 | ($761.24) | ($1,148.17) | ($1,251.06) | ($1,289.75) | ($1,309.22) |
| $50/ton | $2,116.86 | ($27.06) | ($681.04) | ($932.94) | ($1,058.26) | ($1,137.37) |
| $100/ton | $3,438.41 | $890.66 | ($97.12) | ($535.28) | ($768.89) | ($922.56) |

Table 20. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for low site preparation costs on site index 40 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $1.56 | ($7.13) | ($7.96) | ($8.79) | ($8.88) | ($8.82) |
| $10/ton | $4.14 | ($5.36) | ($7.00) | ($8.23) | ($8.50) | ($8.55) |
| $50/ton | $14.47 | $1.71 | ($3.16) | ($6.00) | ($6.98) | ($7.45) |
| $100/ton | $27.38 | $10.55 | $1.64 | ($3.21) | ($5.08) | ($6.08) |

Table 21. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for high site preparation costs on site index 40 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | ($22.19) | ($30.87) | ($31.70) | ($35.55) | ($36.21) | ($36.15) |
| $10/ton | ($19.60) | ($29.11) | ($30.74) | ($34.99) | ($35.83) | ($35.88) |
| $50/ton | ($9.28) | ($22.04) | ($26.90) | ($32.76) | ($34.31) | ($34.78) |
| $100/ton | $3.63 | ($13.20) | ($22.10) | ($29.97) | ($32.41) | ($33.41) |

Table 22. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for low site preparation costs on site index 50 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $8.68 | ($5.34) | ($7.24) | ($7.42) | ($8.67) | ($8.63) |
| $10/ton | $11.81 | ($3.22) | ($5.92) | ($6.58) | ($8.13) | ($8.23) |
| $50/ton | $24.32 | $5.28 | ($0.65) | ($3.24) | ($5.97) | ($6.60) |
| $100/ton | $39.96 | $15.89 | $5.94 | $0.93 | ($3.28) | ($4.57) |

Table 23. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for high site preparation costs on site index 50 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | ($13.15) | ($28.04) | ($29.94) | ($30.12) | ($35.47) | ($35.43) |
| $10/ton | ($10.03) | ($25.91) | ($28.62) | ($29.28) | ($34.93) | ($35.03) |
| $50/ton | $2.48 | ($17.42) | ($23.35) | ($25.94) | ($32.78) | ($33.40) |
| $100/ton | $18.12 | ($6.80) | ($16.76) | ($21.76) | ($30.08) | ($31.37) |

Table 24. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for low site preparation costs on site index 60 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $20.03 | ($2.47) | ($6.44) | ($6.98) | ($8.47) | ($8.46) |
| $10/ton | $23.84 | $0.21 | ($4.83) | ($5.90) | ($7.81) | ($7.95) |
| $50/ton | $39.05 | $10.95 | $1.60 | ($1.62) | ($5.18) | ($5.90) |
| $100/ton | $58.07 | $24.37 | $9.64 | $3.73 | ($1.90) | ($3.35) |

Table 25. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for high site preparation costs on site index 60 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $0.60 | ($21.66) | ($28.25) | ($28.78) | ($34.84) | ($34.83) |
| $10/ton | $4.40 | ($18.98) | ($26.64) | ($27.71) | ($34.18) | ($34.32) |
| $50/ton | $19.62 | ($8.24) | ($20.21) | ($23.43) | ($31.56) | ($32.28) |
| $100/ton | $38.64 | $5.18 | ($12.17) | ($18.08) | ($28.27) | ($29.72) |

Table 26. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for low site preparation costs on site index 70 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $28.65 | ($0.34) | ($5.69) | ($6.53) | ($6.73) | ($8.08) |
| $10/ton | $32.97 | $2.72 | ($3.74) | ($5.17) | ($5.75) | ($7.39) |
| $50/ton | $50.26 | $14.96 | $4.05 | $0.30 | ($1.84) | ($4.63) |
| $100/ton | $71.87 | $30.26 | $13.80 | $7.14 | $3.05 | ($1.17) |

Table 27. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for high site preparation costs on site index 70 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $10.81 | ($19.12) | ($26.73) | ($27.57) | ($27.76) | ($33.38) |
| $10/ton | $15.13 | ($16.06) | ($24.78) | ($26.20) | ($26.78) | ($32.69) |
| $50/ton | $32.42 | ($3.82) | ($16.98) | ($20.73) | ($22.87) | ($29.93) |
| $100/ton | $54.03 | $11.48 | ($7.24) | ($13.90) | ($17.99) | ($26.47) |

Table 28. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for low site preparation costs on site index 80 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $31.27 | $1.45 | ($4.56) | ($6.03) | ($6.36) | ($6.45) |
| $10/ton | $35.81 | $4.76 | ($2.34) | ($4.46) | ($5.22) | ($5.61) |
| $50/ton | $53.97 | $18.01 | $6.53 | $1.82 | ($0.66) | ($2.22) |
| $100/ton | $76.67 | $34.58 | $17.62 | $9.66 | $5.05 | $2.02 |

Table 29. Net revenue (or cost) for every ton of carbon stored with timber management and carbon credits for high site preparation costs on site index 80 (base age 50) West Virginia abandoned mine lands planted with northern red oak.

| | Alternative Rates of Return | | | | | |
|---|---|---|---|---|---|---|
| Carbon Price | 0.5% | 2.5% | 5.0% | 7.5% | 10.0% | 12.5% |
| $0/ton | $13.66 | ($17.05) | ($24.02) | ($26.25) | ($26.59) | ($26.68) |
| $10/ton | $18.20 | ($13.74) | ($21.80) | ($24.68) | ($25.45) | ($25.83) |
| $50/ton | $36.36 | ($0.49) | ($12.93) | ($18.41) | ($20.88) | ($22.44) |
| $100/ton | $59.07 | $16.08 | ($1.84) | ($10.56) | ($15.17) | ($18.20) |

Site Index 40

<u>0.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 0.5% requires only a final harvest at age 100 (Table 2). The optimal timber management regime would yield an SEV of $628.09 per acre (Table 3) with a corresponding $NPW_T$ of $67.28 per acre (Table 5) when site preparation costs are low. An SEV of -$396.91 per acre (Table 4) with a corresponding $NPW_T$ of -$957.72 per acre (Table 6) could be earned when site preparation costs are high. These values show that a landowner with low site preparation costs could earn 0.5% on every dollar invested plus $67.28 per acre over one rotation, or $628.09 per acre over an infinite series of rotations. When site preparation costs are high, a landowner would earn 0.5% on every dollar invested plus -$957.72 per acre over one rotation, or -$396.91 per acre over an infinite series of rotations.

With this optimal rotation, 43 tons of carbon could be stored per acre (Table 7) with a cost per ton of carbon stored (total cost divided by the total tons of carbon stored) of $12.94 when site preparation costs are low and $36.68 when site preparation costs are high (Tables 8 and 9, respectively). When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be $67.28, $178.74, $624.58, and $1,181.88, respectively (Table 10). The per acre $NPW_{T+C}$ with high site preparation costs would be -$957.72, -$846.26, -$400.42, and $156.88, respectively (Table 11).

The net revenue (or cost) for every ton of carbon stored ($NPW_{T+C}$ divided by the total tons of carbon stored) when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are $1.56, $4.14, $14.47, and $27.38, respectively (Table 20). The net revenue would be -$22.19, -$19.60, -$9.28, and $3.63, respectively (Table 21), when site preparation costs are high.

<u>2.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 2.5% requires only a final harvest at age 100. The optimal timber management regime would yield an SEV of -$308.55 per acre with a corresponding $NPW_T$ of -$307.85 per acre when site preparation costs are low. An SEV of -$1,333.55 per acre with a corresponding $NPW_T$ of -$1,332.85 per acre could be earned when site preparation costs are high.

With this optimal rotation, 43 tons of carbon could be stored per acre with a cost per ton of carbon stored of $9.15 when site preparation costs are low and $32.90 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$307.85, -$231.53, $73.74, and $455.33, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,332.85, -$1,256.53, -$951.26, and -$569.67, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$7.13, -$5.36, $1.71, and $10.55, respectively. The net revenue would be -$30.87, -$29.11, -$22.04, and -$13.20, respectively, when site preparation costs are high.

<u>5.0% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 5.0% requires only a final harvest at age 100. The optimal timber management regime would yield an SEV of -$343.90 per acre with a corresponding $NPW_T$ of -$343.59 per acre when site preparation costs are low. An SEV of -$1,368.90 per acre with a corresponding $NPW_T$ of -$1,368.59 per acre could be earned when site preparation costs are high.

With this optimal rotation, 43 tons of carbon could be stored per acre with a cost per ton of carbon stored of $8.14 when site preparation costs are low and $31.89 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$343.59, -$302.14, -$136.35, and $70.89, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,368.59, -$1,327.14, -$1,161.35, and -$954.11, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$7.96, -$7.00, -$3.16, and $1.64, respectively. The net revenue would be -$31.70, -$30.74, -$26.90, and -$22.10, respectively, when site preparation costs are high.

<u>7.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 7.5% requires only a final harvest at age 48. The optimal timber management regime would yield an SEV of -\$337.65 per acre with a corresponding $NPW_T$ of -\$336.56 per acre when site preparation costs are low. An SEV of -\$1,362.65 per acre with a corresponding $NPW_T$ of -\$1,361.56 per acre could be earned when site preparation costs are high.

With this optimal rotation, 38 tons of carbon could be stored per acre with a cost per ton of carbon stored of \$8.83 when site preparation costs are low and \$35.59 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$336.56, -\$315.20, -\$229.76, and -\$122.96, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,361.56, -\$1,340.20, -\$1,254.76, and -\$1,147.96, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$8.79, -\$8.23, -\$6.00, and -\$3.21, respectively. The net revenue would be -\$35.55, -\$34.99, -\$32.76, and -\$29.97, respectively, when site preparation costs are high.

<u>10.0% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 10.0% requires only a final harvest at age 43. The optimal timber management regime would yield an SEV of -\$333.59 per acre with a corresponding $NPW_T$ of -\$333.08 per acre when site preparation costs are low. An SEV of -\$1,358.59 per acre with a corresponding $NPW_T$ of -$1,358.08 per acre could be earned when site preparation costs are high.

With this optimal rotation, 38 tons of carbon could be stored per acre with a cost per ton of carbon stored of $8.90 when site preparation costs are low and $36.23 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$333.08, -$318.84, -$261.86, and -$190.64, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,358.08, -$1,343.84, -$1,286.86, and -$1,215.64, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$8.88, -$8.50, -$6.98, and -$5.08, respectively. The net revenue would be -$36.21, -$35.83, -$34.31, and -$32.41, respectively, when site preparation costs are high.

<u>12.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 12.5% requires only a final harvest at age 43. The optimal timber management regime would yield an SEV of -$331.12 per acre with a corresponding $NPW_T$ of -$330.95 per acre when site preparation costs are low. An SEV of -$1,356.12 per acre with a corresponding $NPW_T$ of -$1,355.95 per acre could be earned when site preparation costs are high.

With this optimal rotation, 38 tons of carbon could be stored per acre with an average cost per ton of carbon stored of $8.83 when site preparation costs are low and \$36.16 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$330.95, -\$320.64, -\$279.41, and -\$227.87, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,355.95, -\$1,345.64, -\$1,304.41, and -\$1,252.87, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$8.82, -\$8.55, -\$7.45, and -\$6.08, respectively. The net revenue would be -\$36.15, -\$35.88, -\$34.78, and -\$33.41, respectively, when site preparation costs are high.

When the real ARR is below 5.0%, the SEVs and NPWs from timber management only decrease as ARR increases. However, when the real ARR is above 5.0%, the SEVs and NPWs from timber management only increases as ARR increases. This trend is not typical. Typically, as ARR increases profitability decreases. This anomaly occurs when non-normal cash flows are present. In the case of these AML sites, sufficiently high costs, occurring mainly at the beginning of the rotation, are associated with low timber revenues due to the poor site quality. This anomaly also occurs on site index 50 land when the real ARR is greater then 7.5%, and on site index 60 land when the real ARR is greater than 10.0%.

Site Index 50

0.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 0.5% requires a first thinning at age 58 with a 40% basal area removal from below and a final harvest at age 97. The optimal timber management regime would yield an SEV of $1,530.08 per acre with a corresponding $NPW_T$ of $407.55 per acre when site preparation costs are low. An SEV of $505.08 per acre with a corresponding $NPW_T$ of -$617.45 per acre could be earned when site preparation costs are high.

With this optimal rotation, 47 tons of carbon could be stored per acre with a cost per ton of carbon stored of $12.16 when site preparation costs are low and $33.97 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be $407.55, $554.77, $1,143.64, and $1,879.72, respectively (Table 12). The per acre $NPW_{T+C}$ with high site preparation costs would be -$617.45, -$470.23, $118.64, and $854.72, respectively (Table 13). The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are $8.68, $11.81, $24.32, and $39.96, respectively (Table 22). The net revenue would be -$13.15, -$10.03, $2.48, and $18.12, respectively (Table 23), when site preparation costs are high.

2.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 2.5% requires a first thinning at age 58 with a 40% basal area removal from below and a final harvest at age 76. The optimal timber management regime would yield an SEV of -$230.85 per acre with a corresponding $NPW_T$ of -$241.18 per acre when site preparation costs are low. An SEV of -$1,255.85 per acre with a corresponding $NPW_T$ of -$1,266.18 per acre could be earned when site preparation costs are high.

With this optimal rotation, 45 tons of carbon could be stored per acre with a cost per ton of carbon stored of $8.65 when site preparation costs are low and $31.34 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$241.18, -$145.28, $283.30, and $717.77, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,266.18, -$1,170.28, -$786.70, and -$307.23, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$5.34, -$3.22, $5.28, and $15.89, respectively. The net revenue would be -$28.04, -$25.91, -$17.42, and -$6.80, respectively, when site preparation costs are high.

5.0% Real ARR

The optimal rotation setting when a landowner's real ARR is 5.0% requires a first thinning at age 58 with a 40% basal area removal from below and a final harvest at age 76. The optimal timber management regime would yield an SEV of -$327.68 per acre with a corresponding $NPW_T$ of -$327.04 per acre when site preparation costs are low. An SEV of -$1,352.68 per acre with a corresponding $NPW_T$ of -$1,352.04 per acre could be earned when site preparation costs are high.

With this optimal rotation, 45 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.79 when site preparation costs are low and $30.49 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$327.04, -$267.51, -$29.39, and $268.26, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,352.04, -$1,292.51, -$1,054.39, and -$756.74, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$7.24, -$5.92, -$0.65, and $5.94, respectively. The net revenue would be -$29.94, -$28.62, -$23.35, and -$16.76, respectively, when site preparation costs are high.

<u>7.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 7.5% requires a first thinning at age 58 with a 40% basal area removal from below and a final harvest at age 76. The optimal timber management regime would yield an SEV of -$335.23 per acre with a corresponding $NPW_T$ of -$335.09 per acre when site preparation costs are low. An SEV of -$1,360.23 per acre with a corresponding

$NPW_T$ of -$1,360.09 per acre could be earned when site preparation costs are high.

With this optimal rotation, 45 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.52 when site preparation costs are low and $30.21 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$335.09, -$297.36, -$146.46, and $42.17, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,360.09, -$1,322.36, -$1,171.46, and -$982.83, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$7.42, -$6.58, -$3.24, and $0.93, respectively. The net revenue would be -$30.12, -$29.28, -$25.94, and -$21.76, respectively, when site preparation costs are high.

10.0% Real ARR

The optimal rotation setting when a landowner's real ARR is 10.0% requires only a final harvest at age 33. The optimal timber management regime would yield an SEV of -$332.79 per acre with a corresponding $NPW_T$ of -$331.51 per acre when site preparation costs are low. An SEV of -$1,357.79 per acre with a corresponding $NPW_T$ of -$1,356.51 per acre could be earned when site preparation costs are high.

With this optimal rotation, 38 tons of carbon could be stored per acre with a cost per ton of carbon stored of $8.72 when site preparation costs are low and

\$35.52 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$331.51, -\$310.91, -\$228.51, and -\$125.50, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,356.51, -\$1,335.91, -\$1,253.51, and -\$1,150.50, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$8.67, -\$8.13, -\$5.97, and -\$3.28, respectively. The net revenue would be -\$35.47, -\$34.93, -\$32.78, and -\$30.08, respectively, when site preparation costs are high.

<u>12.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 12.5% requires only a final harvest at age 33. The optimal timber management regime would yield an SEV of -\$330.72 per acre with a corresponding $NPW_T$ of -\$330.16 per acre when site preparation costs are low. An SEV of -\$1,355.72 per acre with a corresponding $NPW_T$ of -\$1,355.16 per acre could be earned when site preparation costs are high.

With this optimal rotation, 38 tons of carbon could be stored per acre with a cost per ton of carbon stored of \$8.66 when site preparation costs are low and \$35.46 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$330.16, -\$314.61, -\$252.40, and -\$174.64, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,355.16,

-$1,339.61, -$1,277.40, and -$1,199.64, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$8.63, -$8.23, -$6.60, and -$4.57, respectively. The net revenue would be -$35.43, -$35.03, -$33.40, and -$31.37, respectively, when site preparation costs are high.

## Site Index 60

### 0.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 0.5% requires a first thinning at age 57, a second thinning at age 69 (with a 30% basal area removal from below for both thinnings), and a final harvest at age 98. The optimal timber management regime would yield an SEV of $3,181.49 per acre with a corresponding $NPW_T$ of $1,056.66 per acre when site preparation costs are low. An SEV of $2,156.49 per acre with a corresponding $NPW_T$ of $31.66 per acre could be earned when site preparation costs are high.

With this optimal rotation, 53 tons of carbon could be stored per acre with a cost per ton of carbon stored of $12.21 when site preparation costs are low and $31.64 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be $1,056.66, $1,257.32, $2,059.98, and $3,063.30, respectively (Table 14). The per acre $NPW_{T+C}$ with high site preparation costs would be

$31.66, $232.32, $1,034.98, and $2,038.30, respectively (Table 15). The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are $20.03, $23.84, $39.05, and $58.07, respectively (Table 24). The net revenue would be $0.60, $4.40, $19.62, and $38.64, respectively (Table 25), when site preparation costs are high.

2.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 2.5% requires a first thinning at age 57, a second thinning at age 68 (with a 30% basal area removal from below for both thinnings), and a final harvest at age 96. The optimal timber management regime would yield an SEV of -$112.78 per acre with a corresponding $NPW_T$ of -$129.85 per acre when site preparation costs are low. An SEV of -$1,137.78 per acre with a corresponding $NPW_T$ of -$1,154.85 per acre could be earned when site preparation costs are high.

With this optimal rotation, 53 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.83 when site preparation costs are low and $27.35 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$129.85, $11.13, $575.03, and $1,279.90, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,137.78, -$996.80, -$432.90, and $271.97, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -\$2.47, \$0.21, \$10.95, and \$24.37, respectively. The net revenue would be -\$21.66, -\$18.98, -\$8.24, and \$5.18, respectively, when site preparation costs are high.

<u>5.0% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 5.0% requires a first thinning at age 43 with a 40% basal area removal from below and a final harvest at age 63. The optimal timber management regime would yield an SEV of -\$302.87 per acre with a corresponding $NPW_T$ of -\$302.74 per acre when site preparation costs are low. An SEV of -\$1,327.87 per acre with a corresponding $NPW_T$ of -\$1,327.74 per acre could be earned when site preparation costs are high.

With this optimal rotation, 47 tons of carbon could be stored per acre with a cost per ton of carbon stored of \$7.52 when site preparation costs are low and \$29.33 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$302.74, -\$227.18, \$75.08, and \$452.91, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,327.74, -\$1,252.18, -\$949.92, and -\$572.09, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$6.44, -\$4.83, \$1.60, and \$9.64, respectively. The net revenue would be -\$28.25, -\$26.64, -\$20.21, and -\$12.17, respectively, when site preparation costs are high.

7.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 7.5% requires a first thinning at age 43 with a 40% basal area removal from below and a final harvest at age 63. The optimal timber management regime would yield an SEV of -$328.13 per acre with a corresponding $NPW_T$ of -$327.85 per acre when site preparation costs are low. An SEV of -$1,353.13 per acre with a corresponding $NPW_T$ of -$1,352.85 per acre could be earned when site preparation costs are high.

With this optimal rotation, 47 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.24 when site preparation costs are low and $29.04 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$327.85, -$277.52, -$76.21, and $175.44, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,352.85, -$1,302.52, -$1,101.21, and -$849.56, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$6.98, -$5.90, -$1.62, and $3.73, respectively. The net revenue would be -$28.78, -$27.71, -$23.43, and -$18.08, respectively, when site preparation costs are high.

10.0% Real ARR

The optimal rotation setting when a landowner's real ARR is 10.0% requires only a final harvest at age 27. The optimal timber management regime would yield an SEV of -\$331.21 per acre with a corresponding $NPW_T$ of -\$329.05 per acre when site preparation costs are low. An SEV of -\$1,356.21 per acre with a corresponding $NPW_T$ of -\$1,354.05 per acre could be earned when site preparation costs are high.

With this optimal rotation, 39 tons of carbon could be stored per acre with a cost per ton of carbon stored of \$8.56 when site preparation costs are low and \$34.93 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$329.05, -\$303.54, -\$201.48, and -\$73.90, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,354.05, -\$1,328.54, -\$1,226.48, and -\$1,098.90, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$8.47, -\$7.81, -\$5.18, and -\$1.90, respectively. The net revenue would be -\$34.84, -\$34.18, -\$31.56, and -\$28.27, respectively, when site preparation costs are high.

<u>12.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 12.5% requires only a final harvest at age 27. The optimal timber management regime would yield an SEV of -\$329.83 per acre with a corresponding $NPW_T$ of -\$328.73 per acre when site preparation costs are low. An SEV of -\$1,354.83 per acre with a corresponding $NPW_T$ of -\$1,353.73 per acre could be earned when site preparation costs are high.

With this optimal rotation, 39 tons of carbon could be stored per acre with a cost per ton of carbon stored of $8.51 when site preparation costs are low and $34.88 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$329.05, -$303.54, -$201.48, and -$73.90, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,353.73, -$1,333.88, -$1,254.49, and -$1,155.26, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$8.46, -$7.95, -$5.90, and -$3.35, respectively. The net revenue would be -$34.83, -$34.32, -$32.28, and -$29.72, respectively, when site preparation costs are high.

## Site Index 70

### 0.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 0.5% requires a first thinning at age 44, a second thinning at age 72 (with a 30% basal area removal from below for both thinnings), and a final harvest at age 99. The optimal timber management regime would yield an SEV of $4,654.70 per acre with a corresponding $NPW_T$ of $1,645.78 per acre when site preparation costs are low. An SEV of $3,629.70 per acre with a corresponding $NPW_T$ of $620.78 per acre could be earned when site preparation costs are high.

With this optimal rotation, 57 tons of carbon could be stored per acre with a cost per ton of carbon stored of $12.35 when site preparation costs are low and $30.19 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be $1,645.78, $1,894.03, $2,887.03, and $4,128.29, respectively (Table 16). The per acre $NPW_{T+C}$ with high site preparation costs would be $620.78, $869.03, $1,862.03, and $3,103.29, respectively (Table 17). The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are $28.65, $32.97, $50.26, and $71.87, respectively (Table 26). The net revenue would be $10.81, $15.13, $32.42, and $54.03, respectively (Table 27), when site preparation costs are high.

<u>2.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 2.5% requires a first thinning at age 44, a second thinning at age 58 (with a 30% basal area removal from below for both thinnings), and a final harvest at age 82. The optimal timber management regime would yield an SEV of $23.12 per acre with a corresponding $NPW_T$ of -$18.50 per acre when site preparation costs are low. An SEV of -$1,001.88 per acre with a corresponding $NPW_T$ of -$1,043.50 per acre could be earned when site preparation costs are high.

With this optimal rotation, 55 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.69 when site preparation costs are low and

$19.12 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$18.50, $148.48, $816.41, and $1,651.32, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,043.50, -$876.52, -$208.59, and $626.32, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$0.34, $2.72, $14.96, and $30.26, respectively. The net revenue would be -$19.12, -$16.06, -$3.82, and $11.48, respectively, when site preparation costs are high.

<u>5.0% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 5.0% requires a first thinning at age 35 with a 40% basal area removal from below and a final harvest at age 55. The optimal timber management regime would yield an SEV of -$275.87 per acre with a corresponding $NPW_T$ of -$277.44 per acre when site preparation costs are low. An SEV of -$1,300.87 per acre with a corresponding $NPW_T$ of -$1,302.44 per acre could be earned when site preparation costs are high.

With this optimal rotation, 49 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.29 when site preparation costs are low and $28.32 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$277.44, -$182.47, $197.41, and $672.27, respectively; the per acre $NPW_{T+C}$ with high site preparation costs would be -$1,302.44, -$1,207.47, -$827.59, and -$352.73, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$5.69, -$3.74, $4.05, and $13.80, respectively. The net revenue would be -$26.73, -$24.78, -$16.98, and -$7.24, respectively, when site preparation costs are high.

<u>7.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 7.5% requires a first thinning at age 35 with a 40% basal area removal from below and a final harvest at age 55. The optimal timber management regime would yield an SEV of -$318.65 per acre with a corresponding $NPW_T$ of -$318.32 per acre when site preparation costs are low. An SEV of -$1,343.65 per acre with a corresponding $NPW_T$ of -$1,343.32 per acre could be earned when site preparation costs are high.

With this optimal rotation, 49 tons of carbon could be stored per acre with a cost per ton of carbon stored of $6.99 when site preparation costs are low and $28.03 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$318.32, -$251.69, $14.81, and $347.94, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,343.32, -$1,276.69, -$1,010.19, and -$677.06, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$6.53, -$5.17, $0.30, and $7.14, respectively. The net revenue would be -$27.57, -$26.20, -$20.73, and -$13.90, respectively, when site preparation costs are high.

<u>10.0% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 10.0% a first thinning at age 35 with a 40% basal area removal from below and a final harvest at age 55. The optimal timber management regime would yield an SEV of -$327.89 per acre with a corresponding $NPW_T$ of -$327.76 per acre when site preparation costs are low. An SEV of -$1,352.89 per acre with a corresponding $NPW_T$ of -$1,352.76 per acre could be earned when site preparation costs are high.

With this optimal rotation, 49 tons of carbon could be stored per acre with a cost per ton of carbon stored of $6.87 when site preparation costs are low and $27.90 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$327.76, -$280.13, -$89.61, and $148.53, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,352.76, -$1,305.13, -$1,114.61, and -$876.47, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$6.73, -$5.75, -$1.84, and $3.05, respectively. The net revenue would be -$27.76, -$26.78, -$22.87, and -$17.99, respectively, when site preparation costs are high.

<u>12.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 12.5% requires only a final harvest at age 25. The optimal timber management regime would yield an SEV of -$328.65 per acre with a corresponding $NPW_T$ of -$327.31 per acre when site preparation costs are low. An SEV of -$1,353.65 per acre with a corresponding $NPW_T$ of -$1,352.31 per acre could be earned when site preparation costs are high.

With this optimal rotation, 41 tons of carbon could be stored per acre with a cost per ton of carbon stored of $8.17 when site preparation costs are low and $33.47 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$327.31, -$299.33, -$187.40, and -$47.49, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,352.31, -$1,324.33, -$1,212.40, and -$1,072.49, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$8.08, -$7.39, -$4.63, and -$1.17, respectively. The net revenue (or cost) would be -$33.38, -$32.69, -$29.93, and -$26.47, respectively, when site preparation costs are high.

Site Index 80

0.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 0.5% requires a first thinning at age 31 with a 40% basal area removal from below and a final harvest at age 90. The optimal timber management regime would yield an SEV of $5,511.72 per acre with a corresponding $NPW_T$ of $1,820.30 per acre when site preparation costs are low. An SEV of $4,486.72 per acre with a corresponding $NPW_T$ of $795.30 per acre could be earned when site preparation costs are high.

With this optimal rotation, 58 tons of carbon could be stored per acre with a cost per ton of carbon stored of $12.52 when site preparation costs are low and $30.12 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be $1,820.30, $2,084.61, $3,141.86, and $4,463.41, respectively (Table 18). The per acre $NPW_{T+C}$ with high site preparation costs would be $795.30, $1,059.61, $2,116.86, and $3,438.41, respectively (Table 19). The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are $31.27, $35.81, $53.97, and $76.67, respectively (Table 28). The net revenue would be $13.66, $18.20, $36.36, and $59.07, respectively (Table 29), when site preparation costs are high.

2.5% Real ARR

The optimal rotation setting when a landowner's real ARR is 2.5% requires a first thinning at age 31 with a 40% basal area removal from below and a final harvest at age 70. The optimal timber management regime would yield an SEV of $159.88 per acre with a corresponding $NPW_T$ of $80.22 per acre when site preparation costs are low. An SEV of -$865.12 per acre with a corresponding $NPW_T$ of -$944.78 per acre could be earned when site preparation costs are high.

With this optimal rotation, 55 tons of carbon could be stored per acre with a cost per ton of carbon stored of $7.70 when site preparation costs are low and $26.20 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be $80.22, $263.76, $997.94, and $1,915.66, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$944.78, -$761.24, -$27.06, and $890.66, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are $1.45, $4.76, $18.01, and $34.58, respectively. The net revenue would be -$17.05, -$13.74, -$0.49, and $16.08, respectively, when site preparation costs are high.

5.0% Real ARR

The optimal rotation setting when a landowner's real ARR is 5.0% requires a first thinning at age 31 with a 40% basal area removal from below and a final harvest at age 57. The optimal timber management regime would yield an SEV of -$236.18 per acre with a corresponding $NPW_T$ of -$239.95 per acre when site preparation costs are low. An SEV of -$1,261.18 per acre with a corresponding $NPW_T$ of -$1,264.95 per acre could be earned when site preparation costs are high.

With this optimal rotation, 53 tons of carbon could be stored per acre with a cost per ton of carbon stored of $6.82 when site preparation costs are low and $26.28 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$239.95, -$123.17, $343.96, and $927.88, respectively; the per acre $NPW_{T+C}$ with high site preparation costs would be -$1,264.95, -$1,148.17, -$681.04, and -$97.12, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$4.56, -$2.34, $6.53, and $17.62, respectively. The net revenue would be -$24.02, -$21.80, -$12.93, and -$1.84, respectively, when site preparation costs are high.

<u>7.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 7.5% requires a first thinning at age 31 with a 40% basal area removal from below and a final harvest at age 49. The optimal timber management regime would yield an SEV of -$305.75 per acre with a corresponding $NPW_T$ of -$305.59 per acre when site preparation costs are low. An SEV of -$1,330.75 per acre with a corresponding

$NPW_T$ of -$1,330.59 per acre could be earned when site preparation costs are high.

With this optimal rotation, 51 tons of carbon could be stored per acre with a cost per ton of carbon stored of $6.74 when site preparation costs are low and $26.96 when site preparation costs are high. When the price of a ton of carbon is set at $0, $10, $50, or $100, the per acre $NPW_{T+C}$ with low site preparation costs would be -$305.59, -$226.06, $92.06, and $489.72, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -$1,330.59, -$1,251.06, -$932.94, and -$535.28, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at $0, $10, $50, or $100 and site preparation costs are low are -$6.03, -$4.46, $1.82, and $9.66, respectively. The net revenue would be -$26.25, -$24.68, -$18.41, and -$10.56, respectively, when site preparation costs are high.

<u>10.0% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 10.0% a first thinning at age 31 with a 40% basal area removal from below and a final harvest at age 49. The optimal timber management regime would yield an SEV of -$322.81 per acre with a corresponding $NPW_T$ of -$322.62 per acre when site preparation costs are low. An SEV of -$1,347.81 per acre with a corresponding $NPW_T$ of -$1,347.62 per acre could be earned when site preparation costs are high.

With this optimal rotation, 51 tons of carbon could be stored per acre with a cost per ton of carbon stored of \$6.61 when site preparation costs are low and \$26.83 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$322.62, -\$264.75, -\$33.26, and \$256.11, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,347.62, -\$1,289.75, -\$1,058.26, and -\$768.89, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$6.36, -\$5.22, -\$0.66, and \$5.05, respectively. The net revenue would be -\$26.59, -\$25.45, -\$20.88, and -\$15.17, respectively, when site preparation costs are high.

<u>12.5% Real ARR</u>

The optimal rotation setting when a landowner's real ARR is 12.5% requires a first thinning at age 31 with a 40% basal area removal from below and a final harvest at age 49. The optimal timber management regime would yield an SEV of -\$327.26 per acre with a corresponding $NPW_T$ of -\$327.18 per acre when site preparation costs are low. An SEV of -\$1,352.26 per acre with a corresponding $NPW_T$ of -\$1,352.18 per acre could be earned when site preparation costs are high.

With this optimal rotation, 51 tons of carbon could be stored per acre with a cost per ton of carbon stored of \$6.54 when site preparation costs are low and \$26.77 when site preparation costs are high. When the price of a ton of carbon is set at \$0, \$10, \$50, or \$100, the per acre $NPW_{T+C}$ with low site preparation costs would be -\$327.18, -\$284.22, -\$112.37, and \$102.44, respectively. The per acre $NPW_{T+C}$ with high site preparation costs would be -\$1,352.18, -\$1,309.22, -\$1,137.37, and -\$922.56, respectively. The net revenue (or cost) for every ton of carbon stored when the price of a ton of carbon is set at \$0, \$10, \$50, or \$100 and site preparation costs are low are -\$6.45, -\$5.61, -\$2.22, and \$2.02, respectively. The net revenue would be -\$26.68, -\$25.83, -\$22.44, and -\$18.20, respectively, when site preparation costs are high.

# DISCUSSION

## Optimal Timber Rotations

For many years foresters and forest economists have tried to answer the two biggest questions forest landowners have regarding their land: 1) How should I manage my land, and 2) How profitable will it be? The only way these questions can be answered is through the determination of the optimal rotation schedule that maximizes the landowner's financial return. However, determination of this schedule is a daunting task due to the large number of possible thinning and harvesting schedules that must be analyzed. This study has developed a revolutionary new tool that allows forest landowners and managers to know exactly when to thin and harvest, how much to remove at each thin, and the profitability of forest management for any species on any site in any region of the U.S. This task has never before been accomplished. For northern red oak grown on West Virginia AML sites, 769,158 economic analyses were conducted in order to determine what the optimal financial thinning and harvesting schedules were.

Why is knowing the optimal thinning and harvesting schedule important to landowners? In the Northeast, for example, it is not uncommon in even-aged stands to have a first thinning at a 30, a second thinning at age 50, and a final harvest at age 80 (removing about 30% of the basal area at each thinning). Following this management regime on AML lands in West Virginia, when site preparation costs are low, a landowner would lose $6.48 per acre over an infinite series of rotations on site index 80 land calculated with a 2.5% real ARR. Using the optimal rotation on this same acre of land would yield a profit of $159.88. This is a $166.36 difference can quickly add up when applied over several acres. Knowing the optimal thinning and harvesting schedule can help landowners reduce some of the uncertainty involved in forest management because they will know 1) if forest management is profitable on their lands, and 2) how their lands should be managed to maximize profits.

## AML Lands and Carbon Sequestration

The profitability of forest management and the total tons of carbon sequestered are highly dependent on the landowner's real ARR and a site's productivity, or site index. Analyses show that as site index increases profitability increases, and as the real ARR increases profitability generally decreases. Results also indicate that as the ARRs increase rotation lengths decrease, reducing the total tons of carbon stored per acre. And as site index increases the total number of tons stored increases.

One question that arose during this study was: How much exactly has to be paid to sequester one ton of carbon in forests? Is it the total costs of timber management divided by the number of tons of carbon stored? Or is it the net revenue from timber management divided by the number of tons of carbon stored? Forest landowners are not in the business of carbon storage. They are in the business of timber management. The benefit of timber management is that revenue is generated from growing and harvesting trees, and any carbon stored is a positive externality of that management. So, does the cost of timber management per ton of carbon stored reflect what a landowner would truly have to pay to sequester that ton of carbon? No, the net revenue per ton of carbon stored would be the best way to capture what would actually be paid by landowners. When the net revenue per ton is positive, carbon sequestration is essentially free and landowners actually make money when storing a ton of carbon. Only when the net revenue per ton is negative does carbon sequestration have a cost associated with it. For AML sites, the net revenue per ton in most cases is negative indicating that there will be a cost associated with carbon sequestration projects. However, the environmental benefits of reclaiming and afforesting these sites could potentially outweigh the cost associated with sequestration.

## Benefits of a Carbon Credit Market

It is important to note that in these analyses only timber and carbon credits were viewed as monetary commodities. No benefits from the positive environmental externalities associated with reclaiming AML lands nor from the reduction of greenhouse gases were included. Even though analyses of AML sites show that in a majority of cases when both timber and carbon credits were included negative returns were earned, the environmental benefits from partnering utility companies and AML landowners could be significant. Establishing a carbon credit type partnership between utility companies and AML landowners is truly a “win-win” situation for both parties as well as for society as a whole.

Utility Company Benefits

Utility companies who take a leading, voluntary role in mitigating their $CO_2$ emissions can help avoid costly governmental taxation or regulation of their emissions while new technologies are developed which will reduce the use of fossil fuels. A carbon credit market established on AML lands is a perfect mitigating tool because of the large number of acres that are currently unused. One major advantage utility companies have by using this land is that the potential high cost associated with land use conversion (such as the case of converting from agricultural land to forestland) is not present. Another advantage utility companies have is that obtaining carbon credits from AML lands could provide them with more than just the needed mitigating benefit of the carbon credit. Certain practices conducted by utility companies (such as strip mining and fossil fuel burning) are seen as negative in the eyes of many groups. If utility companies take an active role in AML reclamation and $CO_2$ reduction, environmental goodwill could be received.

AML Landowner Benefits

The greatest benefit this type of partnership could have for AML landowners is that their lands would be reclaimed and afforested. Afforestation represents a very cost-effective way of reclaiming these sites. Afforestation can provide these landowners with cyclical revenues from timber sales and, when partnered with utility companies, revenue could be earned from the sale of carbon credits. Analyses showed that in most cases forest management alone (carbon price of $0 per tonne) was not profitable. But, when revenues from the sale of carbon credits were added the potential for profitability increased. Afforestation of these sites could also increase property values as well as enhance the recreational opportunities for these landowners. For this reason landowners may be willing to accept a lower rate of return, such as 0.5 or 2.5%, on their investment.

Societal Benefits

Forming a carbon credit partnership on AML lands can be of great benefit to society, both environmentally as well as economically. Reclamation and afforestation of AML lands can provide society with more wildlife habitat, more recreational opportunities, increased soil enhancements, improved water quality, job creation, and reductions of atmospheric $CO_2$. Using a market solution to reduce atmospheric $CO_2$ while reclaiming AML lands could help avoid costly government subsidies not only for greenhouse gas reductions, but also for the reclamation of AML lands. It is for this reason the OSM and the DOE have formed a collaborative agreement to help reclaim AML lands through the use of a carbon credit market.

Every site has specific reclamation needs. For AML lands across the Appalachian coal region, effective reclamation and afforestation requires 1) a thorough understanding of critical species-site relationships and 2) how stumpage prices change across this region. Future analyses will investigate how these species-site relationships and stumpage prices affect profitability and the total tons of carbon sequestered.

# LITERATURE CITED

Ashby, W.C., W.G. Vogel, and N.F. Rogers. 1985. Black Locust in the Reclamation Equation. General Technical Report NE-105. USDA Forest Service. 12 pp.

Birdsey, R.A. 1996. Carbon Storage for Major Forest Types and Regions in the Counterminous United States. P. 1-26 *in* Forests and Global Change: Forest Management Opportunities for Mitigating Carbon Emissions (Vol. 2), Sampson, R.N., and D. Hair. Washington D.C.: American Forests.

Brady, N.C., and R.R. Weil. 1996. The Nature and Properties of Soils. Prentice Hall, Upper Saddle River. 740 pp.

Brown, S., J. Sathaye, M. Cannell, and P.E. Kauppi. 1996. Mitigation of carbon emissions to the atmosphere by forest management. Com. For. Rev. 75(1): 80-91.

Burger, J.A., and J. L. Torbert. 1999. Status of Reforestation Technology: The Appalachian Region. P. 95-108 *in* Proceedings of Enhancement of Reforestation at Surface Coal Mines: Technical Interactive Forum, Vories, K.C., and D. Throgmorton (eds.). Office of Surface Mining.

Burger, J.A. 2002. Personal interview. 15 February 2002.

Caldwell, C.E., C.E. Cordell, and M.E. Farley. 1992. Ohio's Abandoned Mined Lands Reforestation Program: A Decade of Success. P. 725-730 *in* Achieving Land Use Potential Through Reclamation: Proceedings of the 9th Annual National Meeting of the American Society for Surface Mining and Reclamation. American Society for Surface Mining and Reclamation.

Cannell, M.G.R. 1996. Forests as carbon sinks mitigating the greenhouse effect. Com. For. Rev. 75(1): 92-99.

Clark III, A., and J.G. Schroeder. 1986. Weight, Volume, and Physical Properties of Major Hardwood Species in the Southern Appalachian Mountains. Research Paper SE-253. USDA Forest Service. 63 pp.

Council of Economic Advisors. 2001. Economic Report of the President. United States Government Printing Office, Washington, D.C. 402 pp.

Daniels, W.L., and C.E. Zipper. 1997. Creation and Management of Productive Mine Soils. Virginia Cooperative Extension Publication 460-121. Virginia Polytechnic Institute and State University. 12 pp.

Davidson, W. H. 1981. Timber Volumes of Old Pennsylvania Surface Mine Reclamation Plantations. Research Note NE-303. USDA Forest Service. 5 pp.

Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler, and J. Wisniewski. 1994. Carbon Pools and Flux of Global Forest Ecosystems. Science 263: 185-190.

Energy Information Administration (EIA). 1998. Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity. United States Department of Energy. Washington, D.C. 247pp.

Environmental Protection Agency (EPA). 2002. Global Warming – Climate. EPA Global Warming Site. http://yosemite.epa.gov/oar/globalwarming.nsf/ content/climate.html (9 December. 2002).

Faustmann, M. 1849. Berechnung des Werthes welchen Waldboden sowie noch nicht haubare Holzbestände für die Waldwirtschaft besitzen. Allgemeine Forst und Jagd-Zeitung. 25: 441-455. (English translation in Linnard, W., and M. Gane. 1968. Martin Faustmann and the Evolution of Discounted Cash Flow. Commonwealth Forestry Institute Paper 42).

Fletcher, S.R. 2000. 98-2: Global Climate Change Treaty: The Kyoto Protocol. Congressional Research Service Report, National Council for Science and the Environment. http:// www.ncseonline.org/NLE/CRSreports/Climate/ clim-3.cfm (9 December 2002).

Gregory, G.R. 1987. Resource Economics for Foresters. John Wiley & Sons, Inc. New York. 477pp.

Huang, C. 1999. Economic Analysis of Carbon Storage in Loblolly Pine Plantations. Ph. D Dissertation, Stephen F. Austin State Univ., Nacogdoches, Texas. 93 pp.

Intergovermental Panel on Climate Change (IPCCb). 2001. Climate Change 2001: Mitigation. Cambridge University Press, New York. 752 pp.

Intergovermental Panel on Climate Change (IPCCa). 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, New York. 881 pp.

Isebrands, J.G. and R.E. Dickson. 1994. Introduction. P. iii *in* Biology and Silviculture of Northern Red Oak in the North Central Region: a Synopsis. General Technical Report NC-173. USDA Forest Service.

Johnson, D.W. 1992. Effects of Forest Management on Soil Carbon Storage. Water, Air, and Soil Pollution 64: 83-120.

Johnson, P.S. 1994. The Silviculture of Northern Red Oak. P. 33-68 *in* Biology and Silviculture of Northern Red Oak in the North Central Region: a Synopsis. General Technical Report NC-173. USDA Forest Service.

Kimmins, J.P. 1997. Forest Ecology: A Foundation for Sustainable Management. Prentice Hall, Upper Saddle River. 596 pp.

Koch, P. 1989. Estimates by Species Group and Region in the USA of: I. Below-ground Root Weight as a Percentage of Ovendry Complete-tree Weight; and II. Carbon Content of Tree Portions. Unpublished Consulting Report. 23 pp.

Kronrad, G.D. 2002. Personal interview. 15 January 2002.

Plass, W.T. 1977. Growth and Survival of Hardwoods and Pine Interplanted with European Alder. Research Paper NE-376. USDA Forest Service. 10 pp.

Plass, W.T., and J.L. Powell. 1988. Trees and Shrubs. P. 175-199 *in* Reclamation of Surface-Mined Lands: Volume II, Hossner, Lloyd R. (ed). CRC Press, Inc., Boca Raton.

Sander, I.L. 1990. *Quercus rubra* L.: Northern Red Oak. P. 727-733 *in* Silvics of North America: Volume 2. Hardwoods. Agriculture Handbook 654. USDA Forest Service.

Schoenholtz, S.H., and J.A. Burger. 1984. Influence of Cultural Treatments on Survival and Growth of Pines on Strip-Mined Sites. Reclamation and Revegetation Research 3: 223-237.

Sedjo, R.A. 1989. Forets to Offset the Greenhouse Effect. J. of For. 87(7): 12-15.

Sharpe, D.M., and C. Johnson. 1981. Land Use and Carbon Storage in Georgia Forests. J. Environ. Manage. 12: 221-233.

Skousen, J.G., C.D. Johnson, and K. Garbutt. 1994. Natural Vegetation of 15 Abandonded Mine Land Sites in West Virgina. J. Environ. Qual. 23: 1224-1230.

Smith, D.W. 1995. The Southern Appalachian Hardwood Region. P. 173-225 *in* Regional Silviculture of the United States Third Edition, Barrett, J.W. (ed). John Wiley & Sons, Inc., New York.

Speth, J. 1990. Foreword. P.vii-viii *in* Minding the Carbon Store: Weighing U.S. Forestry Strategies to Slow Global Warming. World Resources Institute. Washington, D.C. 81 pp.

Teck, R.M., M. Moeur, and B. Eav. 1996. Forecasting Ecosystems with the Forest Vegetation Simulator. J. of For. 94(12): 7-10.

Trexler, M. 1990. Minding the Carbon Store: Weighing U.S. Forestry Strategies to Slow Global Warming. World Resources Institute. Washington, D.C. 81 pp.

Vogel, W.G. 1977. Revegetation of Surface-Mined Lands in the East. P. 167-172 *in* Forests for People: A Challenge in World Affairs, Proceedings of the Society of American Foresters 1977 National Convention. Society of American Foresters, Washington, D.C.

Vogel, W.G. 1981. A Guide for Revegetating Coal Minesoils in the Eastern United States. General Technical Report NE-68. USDA Forest Service. 190 pp.

United States Department of Agriculture Forest Service (USDA-FS). 2001. U.S. Forest Facts and Historical Trends. FS-696-M. U.S.D.A. Forest Service. 21pp.

United States Department of Energy (US-DOE). 1999. "Carbon sequestration in terrestrial ecosystems." Carbon Sequestration: State of the Science, http://www.fe.doe.gov/coal_power/sequestration/index_rpt.html (7 Mar. 2000).

United States Department of the Interior Office of Surface Mining (USDI-OSM). 2000. Internal documents.

United States Department of the Interior Office of Surface Mining (USDI-OSM).

2001. Abandoned Mined Land Inventory System. http://www.osmre.gov/aml/inven/zamlis.htm (15 Apr. 2001).

United States Department of the Interior Office of Surface Mining (USDI-OSM). 2002. AML Inventory Definitions. http://www.osmre.gov/aml/inven/zqadefin.htm (15 Jan. 2002).

Uzawa, H. 1991. Global Warming Initiatives: The Pacific Rim. P. 275-324 *in* Global Warming: Economic Policy Responses, Dornbusch, R., and J.M. Poterba (eds.). The MIT Press, Cambridge, MA.

West Virginia Division of Forestry. 1997-2001. West Virginia Timber Price Report.

# APPENDIX

Biological data (per acre) of the optimal rotation settings for northern red oak planted on West Virginia abandoned mine lands.

Table 30. Biological data (per acre) of the optimal rotation schedule for site index 40 (base 50) and real ARR 0.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 100 | Final Harvest | 95.26 | 149.23 | 11.29 | 9.69 | 11.30 | 50.25 | 13.71 | 2,549.61 |

Table 31. Biological data (per acre) of the optimal rotation schedule for site index 40 (base 50) and real ARR 2.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 100 | Final Harvest | 95.26 | 149.23 | 11.29 | 9.69 | 11.30 | 50.25 | 13.71 | 2,549.61 |

Table 32. Biological data (per acre) of the optimal rotation schedule for site index 40 (base 50) and real ARR 5.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 100 | Final Harvest | 95.26 | 149.23 | 11.29 | 9.69 | 11.30 | 50.25 | 13.71 | 2,549.61 |

Table 33. Biological data (per acre) of the optimal rotation schedule for site index 40 (base 50) and real ARR 7.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 48 | Final Harvest | 64.27 | 211.59 | 7.68 | 7.06 | 7.69 | 39.21 | 7.58 | 0.00 |

Table 34. Biological data (per acre) of the optimal rotation schedule for site index 40 (base 50) and real ARR 10.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 43 | Final Harvest | 58.31 | 220.14 | 7.13 | 6.68 | 7.14 | 37.14 | 6.86 | 0.00 |

Table 35. Biological data (per acre) of the optimal rotation schedule for site index 40 (base 50) and real ARR 12.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 43 | Final Harvest | 58.31 | 220.14 | 7.13 | 6.68 | 7.14 | 37.14 | 6.86 | 0.00 |

Table 36. Biological data (per acre) of the optimal rotation schedule for site index 50 (base 50) and real ARR 0.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 58 | Before 1st Thin | 88.23 | 194.80 | 9.55 | 8.18 | 9.56 | 53.63 | | |
| | After 1st Thin | 52.94 | 106.27 | 9.66 | 9.65 | 9.66 | 54.01 | 6.24 | 0.00 |
| 97 | Final Harvest | 74.72 | 87.29 | 12.53 | 12.52 | 12.54 | 63.20 | 8.95 | 4,018.36 |

Table 37. Biological data (per acre) of the optimal rotation setting, schedule for site index 50 (base 50) and real ARR 2.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 58 | Before 1st Thin | 88.23 | 194.80 | 9.55 | 8.18 | 9.56 | 53.63 | | |
| | After 1st Thin | 52.94 | 106.27 | 9.66 | 9.65 | 9.66 | 54.01 | 6.24 | 0.00 |
| 76 | Final Harvest | 65.14 | 96.60 | 11.12 | 11.12 | 11.13 | 59.05 | 8.92 | 2,327.39 |

Table 38. Biological data (per acre) of the optimal rotation schedule for site index 50 (base 50) and real ARR 5.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 58 | Before 1st Thin | 88.23 | 194.80 | 9.55 | 8.18 | 9.56 | 53.63 | | |
| | After 1st Thin | 52.94 | 106.27 | 9.66 | 9.65 | 9.66 | 54.01 | 6.24 | 0.00 |
| 76 | Final Harvest | 65.14 | 96.60 | 11.12 | 11.12 | 11.13 | 59.05 | 8.92 | 2,327.39 |

Table 39. Biological data (per acre) of the optimal rotation setting, schedule for site index 50 (base 50) and real ARR 7.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 58 | Before 1st Thin | 88.23 | 194.80 | 9.55 | 8.18 | 9.56 | 53.63 | | |
| | After 1st Thin | 52.94 | 106.27 | 9.66 | 9.65 | 9.66 | 54.01 | 6.24 | 0.00 |
| 76 | Final Harvest | 65.14 | 96.60 | 11.12 | 11.12 | 11.13 | 59.05 | 8.92 | 2,327.39 |

Table 40. Biological data (per acre) of the optimal rotation schedule for site index 50 (base 50) and real ARR 10.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 33 | Final Harvest | 60.23 | 243.23 | 6.97 | 6.32 | 6.98 | 41.00 | 7.08 | 0.00 |

Table 41. Biological data (per acre) of the optimal rotation schedule for site index 50 (base 50) and real ARR 12.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 33 | Final Harvest | 60.23 | 243.23 | 6.97 | 6.32 | 6.98 | 41.00 | 7.08 | 0.00 |

Table 42. Biological data (per acre) of the optimal rotation setting, schedule for site index 60 (base 50) and real ARR 0.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 57 | Before 1st Thin | 98.76 | 189.46 | 10.30 | 8.45 | 10.51 | 63.38 | | |
| | After 1st Thin | 69.13 | 117.65 | 10.39 | 10.39 | 10.59 | 63.74 | 6.06 | 0.00 |
| 69 | Before 2nd Thin | 77.73 | 108.90 | 11.27 | 11.26 | 11.78 | 67.65 | | |
| | After 2nd Thin | 54.41 | 75.07 | 11.73 | 11.37 | 11.89 | 68.02 | 4.08 | 831.51 |
| 98 | Final Harvest | 77.31 | 65.01 | 14.68 | 13.74 | 16.23 | 76.80 | 8.58 | 6,207.34 |

Table 43. Biological data (per acre) of the optimal rotation setting, schedule for site index 60 (base 50) and real ARR 2.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 57 | Before 1st Thin | 98.76 | 189.46 | 10.30 | 8.45 | 10.51 | 63.38 | | |
| | After 1st Thin | 69.13 | 117.65 | 10.39 | 10.39 | 10.59 | 63.74 | 6.06 | 0.00 |
| 68 | Before 2nd Thin | 77.20 | 109.59 | 11.19 | 11.18 | 11.71 | 67.37 | | |
| | After 2nd Thin | 54.04 | 75.54 | 11.66 | 11.30 | 11.81 | 67.74 | 4.19 | 750.26 |
| 96 | Final Harvest | 76.45 | 65.68 | 14.45 | 13.61 | 16.10 | 76.39 | 7.91 | 6,125.18 |

Table 44. Biological data (per acre) of the optimal rotation schedule for site index 60 (base 50) and real ARR 5.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 43 | Before 1st Thin | 85.83 | 217.15 | 9.00 | 7.57 | 9.01 | 57.06 | | |
| | After 1st Thin | 51.50 | 116.56 | 9.12 | 9.12 | 9.21 | 57.79 | 6.04 | 0.00 |
| 63 | Final Harvest | 69.98 | 102.43 | 11.05 | 11.04 | 11.38 | 66.26 | 12.24 | 2,497.34 |

Table 45. Biological data (per acre) of the optimal rotation schedule for site index 60 (base 50) and real ARR 7.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 43 | Before 1st Thin | 85.83 | 217.15 | 9.00 | 7.57 | 9.01 | 57.06 | | |
| | After 1st Thin | 51.50 | 116.56 | 9.12 | 9.12 | 9.21 | 57.79 | 6.04 | 0.00 |
| 63 | Final Harvest | 69.98 | 102.43 | 11.05 | 11.04 | 11.38 | 66.26 | 12.24 | 2,497.34 |

Table 46. Biological data (per acre) of the optimal rotation schedule for site index 60 (base 50) and real ARR 10.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 27 | Final Harvest | 61.56 | 257.69 | 6.92 | 6.08 | 6.94 | 44.24 | 7.23 | 0.00 |

Table 47. Biological data (per acre) of the optimal rotation schedule for site index 60 (base 50) and real ARR 12.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 27 | Final Harvest | 61.56 | 257.69 | 6.92 | 6.08 | 6.94 | 44.24 | 7.23 | 0.00 |

Table 48. Biological data (per acre) of the optimal rotation schedule for site index 70 (base 50) and real ARR 0.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 44 | Before 1st Thin | 95.91 | 210.35 | 9.68 | 7.98 | 9.69 | 67.64 | | |
| | After 1st Thin | 67.14 | 131.30 | 9.79 | 9.79 | 9.80 | 68.22 | 6.02 | 0.00 |
| 72 | Before 2nd Thin | 87.98 | 106.29 | 12.07 | 12.06 | 13.05 | 80.07 | | |
| | After 2nd Thin | 61.59 | 73.05 | 12.26 | 12.18 | 13.34 | 80.51 | 4.07 | 1,409.97 |
| 99 | Final Harvest | 84.61 | 62.45 | 14.49 | 14.34 | 19.31 | 90.03 | 9.56 | 8,485.91 |

Table 49. Biological data (per acre) of the optimal rotation schedule for site index 70 (base 50) and real ARR 2.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 44 | Before 1st Thin | 95.91 | 210.35 | 9.68 | 7.98 | 9.69 | 67.64 | | |
| | After 1st Thin | 67.14 | 131.30 | 9.79 | 9.79 | 9.80 | 68.22 | 6.02 | 0.00 |
| 58 | Before 2nd Thin | 78.96 | 117.74 | 11.01 | 11.00 | 11.31 | 74.72 | | |
| | After 2nd Thin | 55.27 | 81.87 | 11.13 | 11.13 | 11.43 | 75.26 | 4.98 | 807.01 |
| 82 | Final Harvest | 76.45 | 70.89 | 13.43 | 13.43 | 14.91 | 85.36 | 9.02 | 6,243.14 |

Table 50. Biological data (per acre) of the optimal rotation schedule for site index 70 (base 50) and real ARR 5.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 35 | Before 1st Thin | 85.81 | 233.26 | 8.68 | 7.28 | 8.69 | 61.72 | | |
| | After 1st Thin | 51.48 | 125.30 | 8.83 | 8.82 | 8.84 | 62.58 | 6.03 | 0.00 |
| 55 | Final Harvest | 71.41 | 107.48 | 11.04 | 11.03 | 11.04 | 74.00 | 14.80 | 2,555.29 |

Table 51. Biological data (per acre) of the optimal rotation schedule for site index 70 (base 50) and real ARR 7.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 35 | Before 1st Thin | 85.81 | 233.26 | 8.68 | 7.28 | 8.69 | 61.72 | | |
| | After 1st Thin | 51.48 | 125.30 | 8.83 | 8.82 | 8.84 | 62.58 | 6.03 | 0.00 |
| 55 | Final Harvest | 71.41 | 107.48 | 11.04 | 11.03 | 11.04 | 74.00 | 14.80 | 2,555.29 |

Table 52. Biological data (per acre) of the optimal rotation schedule for site index 70 (base 50) and real ARR 10.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 35 | Before 1st Thin | 85.81 | 233.26 | 8.68 | 7.28 | 8.69 | 61.72 | | |
| | After 1st Thin | 51.48 | 125.30 | 8.83 | 8.82 | 8.84 | 62.58 | 6.03 | 0.00 |
| 55 | Final Harvest | 71.41 | 107.48 | 11.04 | 11.03 | 11.04 | 74.00 | 14.80 | 2,555.29 |

Table 53. Biological data (per acre) of the optimal rotation schedule for site index 70 (base 50) and real ARR 12.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 25 | Final Harvest | 68.03 | 263.81 | 7.22 | 6.25 | 7.23 | 52.70 | 10.13 | 0.00 |

Table 54. Biological data (per acre) of the optimal rotation schedule for site index 80 (base 50) and real ARR 0.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 31 | Before 1st Thin | 86.77 | 238.63 | 8.66 | 7.17 | 8.67 | 66.90 | | |
| | After 1st Thin | 52.06 | 127.19 | 8.83 | 8.83 | 8.84 | 68.01 | 6.11 | 0.00 |
| 90 | Final Harvest | 99.58 | 77.98 | 14.13 | 14.12 | 24.09 | 97.76 | 10.92 | 10,535.27 |

Table 55. Biological data (per acre) of the optimal rotation schedule for site index 80 (base 50) and real ARR 2.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 31 | Before 1st Thin | 86.77 | 238.63 | 8.66 | 7.17 | 8.67 | 66.9 | | |
| | After 1st Thin | 52.06 | 127.19 | 8.83 | 8.83 | 8.84 | 68.01 | 6.11 | 0.00 |
| 70 | Final Harvest | 90.62 | 91.56 | 12.84 | 12.84 | 19.43 | 91.65 | 11.78 | 7,310.65 |

Table 56. Biological data (per acre) of the optimal rotation schedule for site index 80 (base 50) and real ARR 5.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 31 | Before 1st Thin | 86.77 | 238.63 | 8.66 | 7.17 | 8.67 | 66.90 | | |
| | After 1st Thin | 52.06 | 127.19 | 8.83 | 8.83 | 8.84 | 68.01 | 6.11 | 0.00 |
| 57 | Final Harvest | 81.03 | 101.66 | 11.81 | 11.81 | 15.79 | 86.05 | 14.24 | 4,628.96 |

Table 57. Biological data (per acre) of the optimal rotation schedule for site index 80 (base 50) and real ARR 7.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 31 | Before 1st Thin | 86.77 | 238.63 | 8.66 | 7.17 | 8.67 | 66.90 | | |
| | After 1st Thin | 52.06 | 127.19 | 8.83 | 8.83 | 8.84 | 68.01 | 6.11 | 0.00 |
| 49 | Final Harvest | 73.74 | 108.52 | 11.04 | 11.04 | 13.23 | 81.65 | 15.09 | 2,738.00 |

Table 56. Biological data (per acre) of the optimal rotation schedule for site index 80 (base 50) and real ARR 10.0%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 31 | Before 1st Thin | 86.77 | 238.63 | 8.66 | 7.17 | 8.67 | 66.90 | | |
| | After 1st Thin | 52.06 | 127.19 | 8.83 | 8.83 | 8.84 | 68.01 | 6.11 | 0.00 |
| 49 | Final Harvest | 73.74 | 108.52 | 11.04 | 11.04 | 13.23 | 81.65 | 15.09 | 2,738.00 |

Table 57. Biological data (per acre) of the optimal rotation schedule for site index 80 (base 50) and real ARR 12.5%.

| Age | Operation | Basal Area (sq. ft.) | Trees per Acre | Avg. DBH (in.) | Min. DBH (in.) | Max. DBH (in.) | Avg. Height (ft.) | Harvested | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cords | Bd. Ft. (Doyle) |
| 31 | Before 1st Thin | 86.77 | 238.63 | 8.66 | 7.17 | 8.67 | 66.90 | | |
| | After 1st Thin | 52.06 | 127.19 | 8.83 | 8.83 | 8.84 | 68.01 | 6.11 | 0.00 |
| 49 | Final Harvest | 73.74 | 108.52 | 11.04 | 11.04 | 13.23 | 81.65 | 15.09 | 2,738.00 |

## VITA

After completing his work at Leander High School, Leander, Texas, in 1992, Richard Bates entered Capital City Trade and Technical School in Austin, Texas. In March of 1993, he received a diploma in Air Conditioning, Heating, Refrigeration, and Appliance Repair, and went on to work in this field for the next two years. The four years following, he attended Stephen F. Austin State University, and in December of 1999 received the degree of Bachelor of Science in Forestry. In January 2000, he entered the Graduate School of Stephen F. Austin State University, and received the degree of Master of Science in Forestry in December of 2002.

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