

INCORPORATING CARBON STORAGE INTO FOREST MANAGEMENT IN MICHIGAN:

A MODELING BASED SCENARIO ANALYSIS

by

Alicia Lindauer-Thompson

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Associate Professor William S. Currie, Chair
Associate Professor Gloria E. Helfand

ABSTRACT

Forest ecosystems play an important role in the global carbon (C) cycle, as they can be both a sink for and a source of atmospheric CO₂. State owned forests in Michigan are dominated by early successional Aspen trees and are frequently managed to maintain Aspen dominance. Here, I developed a model that allows a user to assess the impacts of forest management decisions on forest composition, tree species and size diversity, stand economic value, and C storage. The model, MITRIX, pairs an empirical growth model with a C accounting model and was specifically designed to be useful to forest managers in Michigan to assess the tradeoffs encountered in meeting diverse management goals while incorporating the relatively recent goal of stabilizing or increasing C storage. Inventory and sale data from the Michigan DNR and field data from the University of Michigan Biological Station were obtained for model development and validation. Validation showed that the model accurately simulates forest stand growth and succession. Model simulations suggested that C storage is maximized when an Aspen dominated stand is allowed to succeed to a later successional species cover. If an Aspen stand is to be maintained, increasing the rotation period results in a greater overall C storage. When a landscape-based management approach is taken, timber profits, species diversity, and stand C storage are all stabilized. With a 200 year frame of analysis, the price of C necessary to balance opportunity costs was \$22-26 per metric ton. However, when the time frame of analysis was shortened, this price was considerably higher. The 2008 Michigan state forest plan includes C storage in forest management objectives. The results suggest that considering C storage in Michigan forests will affect stand management decisions and the model described here is a useful tool to assess the impact of altered management strategies.

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INTRODUCTION

Over the past century, atmospheric CO₂ levels have been rising rapidly as a result of anthropogenic activities, including fossil fuel combustion and deforestation (IPCC, 2007). Forest ecosystems have been identified as an important part of the global carbon cycle and have been a component of many of the proposed strategies for mitigation of atmospheric CO₂ emissions (Richards and Stokes, 2004; Neilson *et al.*, 2006). Because the carbon (C) balance of forests is heavily influenced by human action, management of global forest resources will likely play an important role in greenhouse gas reduction strategies.

Forests can be both a sink for and a source of atmospheric CO₂. Aggrading forests act as a sink for atmospheric C as they accumulate biomass in stems, roots, leaves, and understory vegetation and organic matter in soil. The relative proportion of C in each of these pools varies by forest type and geography and can be altered by disturbance and management (Seely *et al.*, 2002; Heath *et al.*, 2003). Approximately 50% of tree dry biomass is C (Masera *et al.*, 2003; Pregitzer and Euskirchen, 2004). Forests can also be a large source of atmospheric CO₂ as C is lost to the atmosphere through respiration, tree mortality, disturbance, and tree harvest. Historically, it was thought that mature forests reach a saturation point when decomposition balances productivity and C uptake slows (Odum, 1969; Law *et al.*, 2003), but recent evidence suggests that old forests continue to act as a net C sink through accumulation of C in soils while holding a large amount of C in the accumulated above and belowground biomass (e.g. Schulze *et al.*, 2000; Carey *et al.*, 2001; U *et al.*, 2004; Zhou *et al.*, 2006). This has important implications for management targeting forest C storage as replacing mature forests with fast growing young plantations will not necessarily result in the greatest net C sink.

Northern temperate forests, which include forest land in the United States, are currently a net sink for atmospheric CO₂ (Birdsey *et al.*, 1993; Huttle *et al.*, 2000; Myneni *et al.*, 2001). United States forest lands have been a net C sink since the early 20th century (Birdsey *et al.*, 2006); and while the net uptake rate has decreased throughout the century, they are predicted to continue to act as a net C sink through the mid 21st century (Birdsey *et al.*, 1993; Myneni *et al.*, 2001). The total ecosystem C stock in temperate forests, which includes C in living biomass, coarse woody debris, organic soil horizons and mineral soil is estimated to be between 130 and 330 Mg C ha⁻¹,

where one megagram (Mg) is equal to 1,000 kg or one metric ton (Pregitzer and Euskirchen, 2004). This stock becomes potentially very significant when the sum across the 1.04 billion ha of northern temperate forest area is considered. C emissions in the United States in 2006 were estimated to be 5.8 million Mg (Energy Information Administration, 2007). In theory, it would take approximately 25,000 ha of additional forest land to offset these emissions, equal to an increase of approximately 0.3% of existing mature forest land in the state of Michigan.

Management and Carbon

Consideration of timber yield and profit, invasive species, pests, disease, wildlife habitat, fire control, and multiple use goals has influenced the way Great Lakes forests are managed (Noss, 2001; Lasch *et al.*, 2005; Spring *et al.*, 2005; Vetter *et al.*, 2005). Management affects many forest attributes including tree diameter distribution (Lin *et al.*, 1996; Buongiorno, 2001; Schwartz *et al.*, 2005; Shao *et al.*, 2005), species composition (Schwartz *et al.*, 2005; Fu *et al.*, 2007), diversity (Eriksson and Hammer, 2006), and amount of litter and coarse woody debris (Alban *et al.*, 1992; Duvall and Grigal, 1999). Forest C stocks are also affected by management decisions that alter the species composition and age structure of the forest. The results of previous studies imply that human management accounts for a greater proportion of change in forest productivity and C storage than environmental change (Caspersen *et al.*, 2000; Schimel *et al.*, 2000; Vetter *et al.*, 2005).

Numerous studies have found a link between management and C storage, with C storage influenced by intensity of harvest as well as the length of the rotation period. Harvest and thinning regimes can differ by percentage of stems removed, method of removal, and degree of disturbance during removal and can affect the diversity and type of trees present. Increasing silviculture intensity has been linked to changes species compositions in temperate plantation forests (Fu *et al.*, 2007), which could have a positive or negative impact on C storage as different tree species hold different amounts of C. A reduction in total ecosystem C, including above and belowground biomass, litter, and soil, was found following the conversion of a natural forest to a tree plantation (Chen *et al.*, 2005). A study modeling the effects of different forest thinning intensities on C storage found that over a 50 year simulation period, heavy thinning of forests resulted in reduced C in both living biomass and soil (Lasch *et al.*, 2005). Management activities

have also been shown to lead to increases in tree biomass, which positively impacts the forest C stock (Vetter *et al.*, 2005). In total, these results suggest that management of forests can impact C storage positively as well as negatively, highlighting the potential importance of management for maximizing the C sink potential of forests.

Harvest intensity can affect C storage in soil and litter via forest floor removal and compaction (Alban *et al.*, 1992) the type of harvest can impact soil C (Johnson and Curtis, 2001; Chen *et al.*, 2005). Changes in rotation period have also been shown to impact C storage, though there is conflicting evidence regarding the direction of the impact. While increasing the rotation period has been shown to lead to an increase in total ecosystem C and an increase in the relative proportion of C in biomass compared to C in soil and litter, shorter rotation periods can lead to an increase in soil C due to inputs from harvest residue (Liski, 2001). In a review of soil C studies, Yanai *et al.* (2003) challenged a commonly used model of soil C storage after forest harvest and suggested that soil C dynamics are strongly affected by the type of harvest, which controls the relative proportion of soil C mixed into the mineral soil versus decomposing into the atmosphere. These findings suggest that the type of management and harvest can have important effects on soil C storage.

Policy Arena

While other countries have begun to include forest management in plans to offset atmospheric CO₂ emissions (e.g. United Nations Bali Conference), the United States has lagged in policy efforts. A mandatory emission trading scheme in the European Union (EU) has led to a number of efforts to quantify effects of forest management on C in order to facilitate the creation of certifiable C credits. In the United States, the current plan to offset CO₂ emissions involves voluntary reporting of emissions. A revision to this voluntary reporting scheme could make a variety of management actions eligible for CO₂ reduction reporting (Birdsey, 2006). Eligible activities could potentially include: reforestation of harvested forestland; afforestation of agricultural land; modified management to increase C sequestration rate or reduce decay rates; lengthening rotation periods; establishment of short rotation biomass plantations; protecting existing forests from harvest or conversion; or low-impact harvesting to decrease emissions from

soil disturbance and resulting post-harvest biomass decay (Richards and Stokes, 2004; Birdsey, 2006).

If the voluntary system of emissions reporting became mandatory or if a C cap and trade system were set into motion, a consideration of C storage in U.S. forest management would be inevitable. If this were to occur, managers would need to consider how various management strategies affect the amount of C stored in a forest stand. Ultimately forest managers will need to balance C storage goals with other priorities. Were C storage to become an actual management priority, a manager might want to consider how different choices affect C storage and how incorporating C storage into management decisions would impact the achievement of other goals. Creation of simple, yet rigorous assessment tools could aid this.

Michigan Forest Management

The state of Michigan has approximately 7.8 million ha of forest cover, which represents approximately 50% of the total land area in the state (Library of Michigan, 2006; Michigan Department of Natural Resources, 2008). Of this, approximately 4.9 million ha are privately owned and managed, 1.2 million ha are federally owned and managed, and 1.6 million ha are owned by the state and managed by the Michigan Department of Natural Resources (DNR), making it one of the largest state forest systems in the country (Michigan Department of Natural Resources, 2008). The state forest land is divided into 15 Forest Management Units (FMUs), each with a designated FMU manager. FMUs are subdivided into compartments, which are units of land between 600-1200 ha in size. Compartments are further divided into stands, which are typically between 4 and 40 ha in size. Stands are identified by a common species composition, age, tree diameter, density, and/or management objective. A stand is the operational unit of the forest and the level where management actions are directed. Each year, approximately one tenth of the compartments in each FMU are inventoried and management actions are prescribed (C. Borgondy, Gladwin FMU Manager, personal communication, 4/6/2007). FMU managers are tasked with prescribing management actions across all stands in a given FMU that simultaneously meet stand and landscape level objectives.

Management goals in Michigan comprise a multiple-use approach and reflect a new widespread understanding of the need to preserve both biodiversity and ecosystem structure

(Schwartz *et al.*, 2005). Specific objectives, as laid out by the state forest plan, are myriad and include maintenance of dominant species, conversion to another cover type, maintenance of diversity or aesthetic character, timber production, and creation or preservation of wildlife habitat (Michigan Department of Natural Resources, 2008). In 2000, there was a shift in state forest management motivation from a sustained yield approach, where the objective is to maximize timber yield while controlling negative environmental impacts, to an ecosystem based approach, where multiple objectives are considered simultaneously (Michigan Department of Natural Resources, 2008). Subsequently in 2004, the Michigan legislature passed a Sustainable Forestry on State Forestlands Act¹, which led the DNR to seek certification through two standards, the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI). This initiated the drafting of a new state forest plan with updated goals and objectives in 2006, which was approved in 2008 (Michigan Department of Natural Resources, 2008). Maintenance of ecosystem services, which include C cycling and storage, is an explicit objective in the new plan; however, as of 2007, C storage was not actively considered when management actions are prescribed at the stand level (C. Borgondy, Gladwin FMU Manager, personal communication, 4/6/2007).

The new state forest plan mandates the simultaneous consideration of multiple goals while managing forest resources in Michigan. One important goal is generating economic activity from state forest lands. Profits from the sale of forest products generate a significant amount of revenue in the state of Michigan (L. Pederson, Forest Planning & Operations Unit Manager, Personal Communication, 5/25/07). The economic productivity of a forest stand is dependent on the amount of profit that can be generated from the sale of wood products as well as by other means such as hunting or recreational fees. Such potential profits can be considered by calculating the present value (PV) of the stand. Among other things the calculated PV is influenced by the degree to which future profits are discounted, or the chosen discount rate for timber sales. To meet the objectives outlined in the new state forest plan, increasing profits must

¹ Public Act 125 of 2004, section 52505

be balanced with other potentially competing objectives such as maintenance of diversity and protection of ecosystem services.

Aspen (*Populus grandidentata* and *P. tremuloides*.) is the dominant species cover in DNR managed forests in Michigan and the second most common species across the state. The percent cover has increased nearly 1000% across the state since 1800 (Michigan Department of Natural Resources, 2008). Aspen trees are economically profitable for pulpwood and Aspen dominated forests provide habitat for many wildlife species including deer and ruffed grouse, which are commonly hunted species in Michigan. For these reasons, maintenance of Aspen dominated forest stands has been a common management objective.

The current strategy for maintaining Aspen stands has created a “boom and bust” legacy in state-owned Michigan forests (Michigan Department of Natural Resources, 2008). As an early successional species, Aspen do not reproduce in their own shade. In the mid to late 1990s, a large number of Aspen stands were harvested to prevent succession to a new cover type (Barnes and Wagner, 2004; Michigan Department of Natural Resources, 2008). This has led to a preponderance of similarly aged Aspen stands across the state. Despite new objectives outlined in the 2008 management plan, maintaining Aspen cover continues to be a motivation for management decisions (Michigan Department of Natural Resources, 2008). In DNR-managed forests across Michigan, Aspen stands are currently managed by clear cutting the stand on a 50-year cycle or rotation period.

In order to maintain a constant supply of mature Aspen for harvest, it has been proposed that an effective management policy would be to harvest 20% of Aspen stands across the state every 10 years, while maintaining a 50 year rotation period for individual stands (Michigan Department of Natural Resources, 2008). This landscape successional mosaic strategy differs from the current strategy as it takes a landscape level perspective in order to stabilize statewide supply and profits. It remains to be determined how the current or newly proposed strategies for Aspen management affect C dynamics in the forest stands. Were increasing C storage to become integrated into management objectives, it would be important to understand the implications for optimal management of Aspen dominated forests.

Forest Models

One of the major challenges with the creation of a new management objective is that theoretical management goals do not always translate into prescriptions made at the stand level. That is, there is often a disconnect between what happens in theory and what happens at the operational level. Considering C storage in Michigan forest management involves setting goals at the landscape level and formulating stand level prescriptions that, together, serve to address the larger goal. One step in aiding this disparity is having a simple tool that allows a manager at the operational level to assess the implications of various management strategies.

Models are frequently used to address questions in forest management. Numerous models have previously been described that address forest growth. These models differ in their purpose, scale, spatial dependence, inclusion of heterogeneity, and state variables among other characteristics (see Porte and Bartelink, 2002 for a review). The type of model best suited for a particular application depends on the amount and level of detail in the data available to the user. The inventory data kept by the Michigan DNR for the state managed forests are coarse in both spatial scale, with details available to the average stand state, and temporal scale, with observations occurring on a decadal time step. Thus, an appropriate model would be simple in form and have relatively few inputs, but still produce realistic predictions of stand growth. One particular class of growth and yield models are stand-based, empirical models of forest growth, which allow a user to assess the impacts of different management decisions on forest stand growth (e.g. Buongiorno and Michie, 1980; Lu and Buongiorno 1993). This model form has yielded relatively good predictions of stand growth in other applications (Lin *et al.*, 1996; Kolbe *et al.*, 1999; Buongiorno, 2001; Namaalwa *et al.*, 2005).

Many models have been developed to account for forest C storage (see e.g. Pinard and Cropper, 2000; Liski, 2001; Seely *et al.*, 2002; Masera *et al.*, 2003; Roxburgh *et al.*, 2006; Garcia-Gonzalo *et al.*, 2007). These models differ in the C pools that they include and are of varying levels of complexity. A C accounting model linked to a growth and yield model is a powerful tool to address the impacts of forest management on C storage. However, to be useful in forest management, the model must match the level of detail available to the user. Management decisions in Michigan are made based on stand level data that identify cohorts of trees by species and size class. An appropriate model to address the implications of

incorporating C storage into Michigan forest management would allow a user to control these two variables.

Research Questions

In this research, a model was developed that allows a user to assess the impacts of forest management decisions on forest composition, tree species and size diversity, stand economic value, and forest C storage. The model, MITRIX, was specifically designed to be useful to FMU managers in Michigan to assess the tradeoffs encountered in meeting diverse management goals and incorporate the relatively recent goal of promoting or maintaining C storage. A simple C accounting model was developed based on a previous effort (Roxburgh *et al.*, 2006) and modified based on available information specific to the region of analysis. MITRIX was used to address the following questions: (1) What are the ecological and economic implications of incorporating C storage into management decisions in state-owned Michigan forests?; and (2) How would incorporating C storage into management goals alter the present management of Aspen dominated forest stands?

METHODS

The model developed in this research combines a matrix based empirical model of stand growth with a mechanistic model of forest C dynamics (Figure 1). The model, MITRIX (MIchigan maTRIX), groups stems by species and diameter class and tracks stem densities (stems ha^{-1}) through time. The model allows a user to assess the impacts of various management strategies on tree species composition, species diversity, stand C storage, and economic value of timber harvests through time. Data from 90 year old unmanaged forest stands at the University of Michigan Biological Station (UMBS) were obtained for validation of model predictions of stand growth and composition in the absence of tree harvest or other management (Appendix I). Inventory data from state DNR managed stands in Michigan were obtained for further validation of model predictions for managed stands. The model was then applied to different management scenarios. The effects of management on C storage, diversity, and stand value were assessed and the implications of including C storage in MI state forest management were addressed.

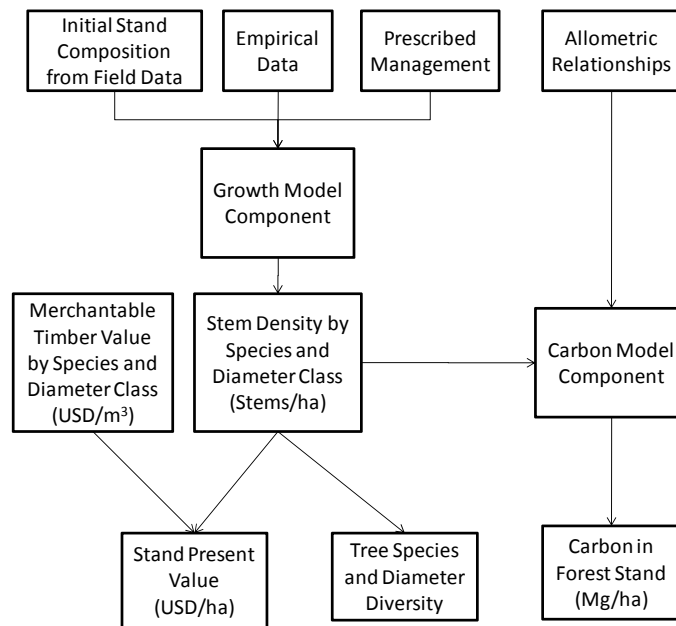


Figure 1. Conceptual flow of information in MITRIX. MITRIX pairs an empirical growth model with a carbon accounting model. Empirical data and management prescriptions feed into the growth component of the model and management actions are prescribed. The model tracks the stem density (stems ha^{-1}) of forest trees through time for each species and diameter class. Tree species and size diversity are calculated with an evenness index (Equation (14)) using the relative stem densities in each diameter class. Stand present value is determined using the value of the merchantable timber, which varies by species and diameter class. The carbon accounting component calculates the amount of C in the stand based on the stem densities and allometric relationships.

Model Development

Growth Model Component

The structure of the growth component of MITRIX was based on a class of matrix models frequently used in forest management applications. The model form was initially proposed by Usher (1969) and modified by Buongiorno and Michie (1980) to allow for analysis of harvest effects. The original model form has been adapted many times and applied to diverse forest types, geographic areas, and analyses. Modeled forest types have included Northern Hardwood forests in Wisconsin, USA (Lu and Buongiorno, 1993; Lin *et al.*, 1996; Buongiorno, 2001), dry woodlands in Uganda (Namaalwa *et al.*, 2005), dipterocarp forests in Southeast Asia (Ingram and Buongiorno, 1996), and mixed broadleaf-conifer forests in China (Shao *et al.*, 2005). Analyses have included stand growth predictions (Namaalwa *et al.*, 2005), effects of management on ecological diversity and/or economic returns (Lu and Buongiorno, 1993; Ingram and Buongiorno, 1996; Lin *et al.*, 1996; Buongiorno, 2001), and identifying optimal stand level cutting intensity to meet landscape level harvest targets (Shao *et al.*, 2005). In the typical model, growth and regeneration are impacted by stem density and stand basal area or girth. Species, when identified, are generally grouped by specific characteristics such as economic value (Lu and Buongiorno, 1993) or shade tolerance (Lin *et al.*, 1996; Kolbe *et al.*, 1999). Atta-Boateng and Moser (1998) provide a method and rationale for grouping species into growth classes when developing growth and yield models. The coefficients for the matrix models are typically based on yield tables rather than process-based, physiological relationships.

MITRIX is based on a model described by Lin *et al.* (1996) and parameterized for Michigan forests by Kolbe *et al.* (1999). The parameters governing MITRIX were set to be fixed, rather than dependent on stand density, in line with previous model formulations (Buongiorno and Michie, 1980; Lu and Buongiorno, 1993; Buongiorno, 2001), which have been shown to predict equally as well as variable parameter formulations (Lin and Buongiorno 1997). Two novel adaptations in MITRIX include the explicit identification of typical dominant tree species in Michigan forests to allow for species specific management as well as decisions by tree diameter class and the addition of a linked C accounting sub-model. Seven unique species and three general classes of trees were included in MITRIX. Species were designated a shade tolerance

class, which determined the parameter values assigned. Shade tolerance was based on properties defined in Barnes and Wagner (2004) (Table 1). Shade tolerant species in the model include American Beech (*Fagus grandifolia*), Red Maple (*Acer rubrum*), and Sugar Maple (*Acer saccharum*). Midtolerant species include Northern Red Oak (*Quercus rubra*) and White Pine (*Pinus strobus*). Shade intolerant species include Aspen (*Populus grandidentata*; *Populus tremuloides*) and Paper Birch (*Betula papyrifera*). All species are common in the forests of Northern Lower Michigan. Three additional general species categories (other shade tolerant, midtolerant, and shade intolerant species) allow for additional species to be included. Nine diameter classes, based on the diameter of a stem at breast height (dbh) or 1.37 m, were included: 1-4.9 cm, 5-9.9 cm, 10-14.9 cm, 15-19.9 cm, 20-24.9 cm, 25-29.9 cm, 30-34.9 cm, 35-39.9 cm, and ≥ 40 cm. The density of stems in each species and size class is tracked through time. MITRIX was further developed by modifying parameters, altering components and simplifying site specifications in order to match the level of detail in the available data.

Table 1. Tree species included in MITRIX. Shade tolerance was based on characterization by Barnes and Wagner (2004).

Shade Tolerance	Common Name	Scientific Name
Tolerant	Red Maple	<i>Acer rubrum</i>
	Sugar Maple	<i>Acer saccharum</i>
	American Birch	<i>Fagus grandifolia</i>
Midtolerant	Red Oak	<i>Quercus rubra</i>
	White Pine	<i>Pinus strobus</i>
Intolerant	Paper or White Birch	<i>Betula papyrifera</i>
	Bigtooth Aspen	<i>Populus grandidentata</i>
	Trembling Aspen	<i>Populus tremuloides</i>

The basic equation governing stem growth tracks the density of stems in each species and size class through time (Equation (1)).

$$\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c} \quad (1)$$

In Equation (1), \mathbf{y}_{t+1} is the stem density (stems ha^{-1}) in each species and size class at time $t+1$; \mathbf{G} is the transition probability matrix, which holds all of the information about whether a stem will move on to the next diameter class (upgrowth), remain in the same diameter class or succumb to mortality between time steps, \mathbf{y}_t is the stem density in each species and size class at

time t ; \mathbf{h}_t is the density of stems harvested at time t ; and \mathbf{c} is the ingrowth, or recruitment, of new trees into the smallest size class, which is independent of stand state.

The transition probability matrix, \mathbf{G} , was constructed from information on mortality, growth, and recruitment. Mortality and growth information were combined to form a matrix, \mathbf{A} . Effects of other trees on the recruitment of new stems are combined into a matrix, \mathbf{R} . The transition probability matrix was then constructed via addition (Equation (2)).

$$\mathbf{G} = \mathbf{A} + \mathbf{R} \quad (2)$$

Growth and Mortality

The \mathbf{A} matrix contains information on tree mortality and upgrowth. The probability that a tree of species i in size class j succumbs to mortality in a time step is represented by d_{ij} , which is affected by the stand basal area, B , and the diameter of the average tree in size class j , D_j (Equation (3)).

$$d_{ij} = \delta_{0i} + \delta_{1i}B + \delta_{2i}D_j + \delta_{3i}D_j^2 \quad (3)$$

The coefficients used in model parameterization, δ_0 , δ_1 , δ_2 , and δ_3 , were taken from Kolbe *et al.* (1999), who obtained them through a regression analysis (Table 2). The coefficient δ_0 is the intercept, which gives the mortality rate independent of stand state. The coefficient δ_1 represents the impact of stand basal area on mortality and δ_2 and δ_3 represent the difference in mortality among diameter classes. The mortality rates were fixed probabilities that differed based on species shade tolerance. Early successional, shade intolerant species have higher mortality rates than late successional species (Mladenoff and He, 1999).

Table 2. Coefficients for mortality equations (Equation (3)) taken from Kolbe *et al.* (1999). δ_0 represents natural mortality independent of stand state, δ_1 represents the impact of stand basal area on mortality, δ_2 and δ_3 represent the difference in mortality among diameter classes.

Coefficients for Mortality Equations				
Species Shade Tolerance:	δ_0	δ_1	δ_2	δ_3
Tolerant	0.034	0.00019	-0.14	0.22
Midtolerant	0.036	0.00052	-0.20	0.27
Intolerant	0.052	0	-0.19	0.22

Upgrowth is the probability that a tree of species i in size class j moves to size class $j + 1$ in a time step. Upgrowth is represented by b_{ij} , which is affected by stand basal area, B , and the diameter of the average tree in size class j , D_j (Equation (4)).

$$b_{ij} = \beta_{0i} + \beta_{1i}B + \beta_{2i}D_j + \beta_{3i}D_j^2, \quad (4)$$

The coefficients used in model parameterization were taken from Kolbe *et al.* (1999) (Table 3). The probability of a tree in size class j remaining in size class j in the next time step is the difference between one and the probability of a tree either moving on the next size class or succumbing to mortality and is represented by a_{ij} (Equation (5)). In Equation (5), n is the number of size classes.

$$a_{ij} = \begin{cases} 1 - b_{ij} - d_{ij}, & \text{for } j < n, \\ a_{ij} = 1 - d_{ij}, & \text{for } j = n \end{cases} \quad (5)$$

Parameters a_{ij} and b_{ij} were combined to form the A matrix, where A_i is the upgrowth of a species i and A is a diagonal matrix containing the A_i matrices for all species (Equation (6)). In Equation (6), m is the number of species.

$$A_i = \begin{bmatrix} a_{i1} & & & & \\ b_{i1} & a_{i2} & & & \\ & b_{i2} & a_{i3} & & \\ & & \dots & & \\ & & & b_{in-1} & a_{in} \end{bmatrix}, \quad A = \begin{bmatrix} A_1 & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & A_2 & & \\ \vdots & & A_3 & \vdots \\ \mathbf{0} & \dots & \mathbf{0} & A_m \end{bmatrix} \quad (6)$$

Table 3. Coefficients for upgrowth equations (Equation (4)) taken from Kolbe *et al.* (1999). Upgrowth is the probability of a stem in size class j moving into size class $j+1$ in a single time step. Here, β_0 represents the stand independent component of upgrowth, β_1 represents the negative impact of present stand basal area, and β_2 and β_3 represent the difference in growth among diameter classes.

Coefficients for Upgrowth Equations				
Species Shade Tolerance:	β_0	β_1	β_2	β_3
Tolerant	0.013	-0.00085	0.23	-0.40
Midtolerant	0.016	-0.0011	0.25	-0.43
Intolerant	0.009	-0.0004	0.21	-0.40

Regeneration processes were not modeled explicitly. Rather, regeneration was represented by ingrowth, which refers to the appearance or new stems in the smallest size class (1 – 4 cm) in a single time step. It is assumed that regeneration is affected by the presence and density of live trees in the stand. The stand independent component of ingrowth, (α_{i0}), defined the recruitment vector, \mathbf{c}_i (Equation (7)). The recruitment vectors for all species were combined to obtain \mathbf{c} in Equation (1).

$$\mathbf{c}_i = \begin{bmatrix} \alpha_{0i} \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad \mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_m \end{bmatrix} \quad (7)$$

Recruitment

The \mathbf{R} matrix was created using information about the effect of existing stems on the survival of new stems entering the smallest size class. Ingrowth was assumed to be positively influenced by the presence of stems of the same species (α_{i1}) and negatively affected by stand basal area (α_{i2}). Coefficients used in the ingrowth equations were taken from Kolbe *et al.* (1999) (Table

4). The effect of species i on the ingrowth of new trees of species k is represented by the matrix R_{ik} . These matrices were combined to get the matrix R according to Equation (8).

$$R_{ik} = \begin{bmatrix} \alpha_{i1}B_1 + \alpha_{i2} & \alpha_{i1}B_2 + \alpha_{i2} & \cdots & \alpha_{i1}B_n + \alpha_{i2} \\ 0 & 0 & \cdots & 0 \\ \vdots & \cdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}, R = \begin{bmatrix} R_{11} & R_{21} & \cdots & R_{m1} \\ R_{12} & R_{22} & & \\ \vdots & & \ddots & \\ R_{1m} & \cdots & & R_{mm} \end{bmatrix} \quad (8)$$

Table 4. Coefficients for ingrowth equations (see Equation 6) taken from Kolbe *et al.* (1999).

Coefficients for Ingrowth Equations			
Species Shade Tolerance:	α_0	α_1	α_2
Tolerant	34	-0.5	0
Midtolerant	12	-0.5	0.004
Intolerant	22	-0.9	0

In addition to stem density, MITRIX tracks the stand basal area through time (Equation (9)).

$$B = \sum_{i=1}^m \sum_{j=1}^n B_{ij} = \sum_{i=1}^m \sum_{j=1}^n y_{ij} \pi \left(\frac{D_j}{2} \right)^2 \quad (9)$$

In Equation (9), B is the stand basal area (m^2ha^{-1}), B_{ij} is the basal area of species i in diameter class j , y_{ij} is the number of stems of species i in diameter class j , and D is the diameter in meters (m) of the average stem in diameter class j .

Carbon Model Component

Output from the growth component informs the carbon sub-model (Figure 1). The conceptual basis for the C dynamics in MITRIX was a C accounting model described by Roxburgh *et al.* (2006) with modifications incorporated. In MITRIX, six C pools were modeled: aboveground biomass, belowground biomass, leaf litter, root litter, coarse woody debris (CWD), and the organic soil layer (Figure 2). The aboveground biomass pool includes stems, branches, and foliage of all live stems. The belowground biomass pool includes the roots of all live stems.

The CWD pool includes standing and fallen dead stems and large stem debris. Because the mineral layer in the soil is a relatively stable pool that is minimally influenced by management or other stand level disturbance and I wanted to be able to assess other components of the C budget without mineral soil effects, only the topmost organic layer of soil C was modeled. I assumed no mixing during harvest or other management. Previous models have taken a similar approach or excluded soil C from analysis (e.g. Backeus *et al.*, 2005; Krcmar *et al.*, 2005; Neilson *et al.*, 2006; Roxburgh *et al.*, 2006).

The input to the C model from the growth model is stem density by species and size class. Living biomass was determined using allometric equations, which take the form

$$Biomass = aD^b \tag{10}$$

where a and b are parameters determined by regressions of field data and D is the diameter of a stem in meters (m). Biomass was converted from organic matter mass in kilograms (kg) to C mass in megagrams (Mg) for ease of comparison to published C values. Parameters are species specific and were obtained from Ter-Mikaelian and Korzukhin (1997) and Perala and Alban (1994), who derived them from tree data in the Upper Great Lakes (Wisconsin, Minnesota, and Michigan) or New Hampshire. Within a size class, stems were assumed to have a j-shaped distribution (many stems with smaller diameters and few stems with larger diameters) typical of natural forests. Given this, and considering that larger stems have an exponentially greater contribution to biomass, a midpoint diameter was used for all stems within a size class. When comparing this method of determining biomass to results from biomass estimates with individual tree data, I found that this method yielded estimates of C within a 2% margin of error.

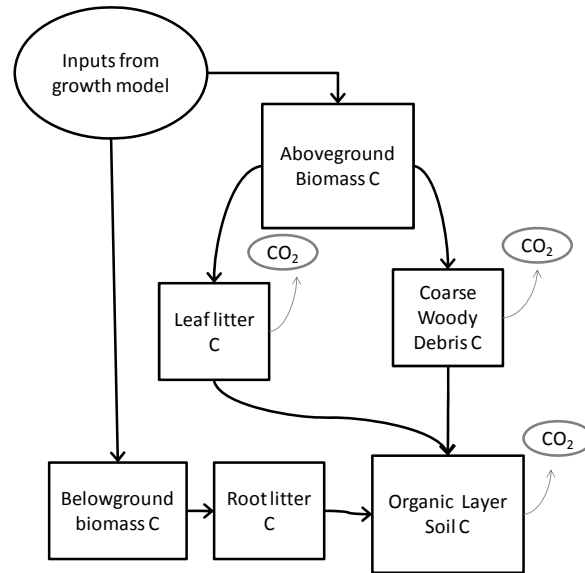


Figure 2. Conceptual model for carbon dynamics. Six carbon pools were modeled: aboveground biomass, belowground biomass, coarse woody debris, leaf litter, root litter, and the organic soil layer. The mineral soil was not modeled and not included in C budget analysis. Aboveground biomass C is 50% of aboveground biomass, which was calculated from allometric relationships applied to the growth model data.

Carbon Pools

C was assumed to be 50% of aboveground biomass (Masera *et al.*, 2003; Pregitzer and Euskirchen, 2004). Belowground biomass was assumed to be 20% of aboveground biomass. While this relationship may vary by geography and forest type, this approximation is within the range of typically modeled relationships (Johnson, 1995; Roxburgh *et al.*, 2006). Root litter was modeled as a function of belowground biomass. The initial value for root litter stock was set to be 15% of initial belowground biomass (Roxburgh *et al.*, 2006). Inputs include roots from recently dead trees, roots from harvested trees, and decay of live roots. Foliar litter was modeled as a function of aboveground biomass. The initial value of foliar litter was set to 1.8 Mg C ha⁻¹ (Alban *et al.*, 1991; Gough *et al.*, 2007b). Leaf litter decay was assumed to be a function of dominant tree species (Table 5).

Inputs to coarse woody debris (CWD) were modeled as a function of tree mortality. The amount of CWD in a forest and the proportion of C within it is dependent on stand age, species present and the specific history of the site (Currie and Nadelhoffer, 2002). In a study in Northern Michigan the mass of CWD was estimated as 1% of total ecosystem C, which includes the mineral soil layer (Gough *et al.*, 2007b), but previous findings suggest that this may be highly

variable. Other studies have estimated the CWD mass in temperate forests to be 18% of total ecosystem C (Pregitzer and Euskirchen, 2004) or as much as 19% of aboveground biomass C, which does not include belowground biomass or mineral soil C (Roxburgh *et al.*, 2006). A study of two different sites in Harvard Forest in New Hampshire dominated by Red Pine and Oak found that C pools in CWD differed by 7 Mg C ha⁻¹ between sites dominated by different species (Currie and Nadelhoffer, 2002). Here, initial stock was set to 2.2 Mg C ha⁻¹ to match the value found for a mature Aspen forest in Northern Michigan (Gough *et al.*, 2007b). Inputs to CWD include newly dead stems. Inputs to the soil organic layer pool include humification of C from leaf litter and CWD and decomposition of root litter.

Decomposition

Decomposition for all C pools was modeled as in Equation (11).

$$C_t = C_0 e^{-kt} \quad (11)$$

In Equation (11), C_t is the amount of C in a given pool at time t , C_0 is the amount of C entering a given pool, and k is the decomposition constant.

Values for decomposition were species specific (Table 5). Because of the lack of available field data, CWD decomposition in MITRIX was set to match decomposition rates of a mature Aspen forest in Northern Michigan (Gough *et al.*, 2007b). This rate was assumed to be the same for all species. Decomposition in the soil organic layer was assumed to be rapid and does not include the portion of C that leaches into the lower soil layers and decomposes slowly. Leaf litter decomposition was modeled in litter cohorts. Each cohort was assumed to decay at a rate determined by the dominant tree species in the stand and the time of cohort initiation. Decomposition constants were estimated based on lignin concentrations. There is an inverse relationship between percent lignin and decomposition because lignin inhibits decomposition ability (Meentemeyer, 1978).

The total C stock of the stand is tracked over the length of the simulation in Mg C ha⁻¹ (12).

$$C_{total} = C_{aboveground} + C_{belowground} + C_{leaf\ litter} + C_{root\ litter} + C_{CWD} + C_{soil} \quad (12)$$

Model Use

In the final model, the user can define the initial stand composition, the length of the simulation, and the prescribed management strategy. Management options include the year of the initial harvest, the rotation period, and the percentage of stems to harvest for each species and size class. When MITRIX is run, it allows the user to observe the effects of a given management strategy on stand composition, species and size class distribution, stem densities, basal area, diversity, and C storage.

Table 5. Table of decomposition constants used in MITRIX.

Constant	Value	Description	Source
k_{cwd}	0.09 year ⁻¹	Coarse woody debris	Gough <i>et al.</i> , 2007
k_{lftit_acru}	0.36 year ⁻¹	<i>Acer rubrum</i> leaf litter	Meentemeyer, 1978 Aber <i>et al.</i> , 1980 Stump and Binkley, 1993 Trofymow <i>et al.</i> , 1995
k_{lftit_acsa}	0.38 year ⁻¹	<i>Acer saccharum</i> leaf litter	Meentemeyer, 1978 Aber <i>et al.</i> , 1980 Stump and Binkley, 1993 Trofymow <i>et al.</i> , 1995
k_{lftit_bepa}	0.34 year ⁻¹	<i>Betula papyrifera</i> leaf litter	Meentemeyer, 1978 Aber <i>et al.</i> , 1980 Stump and Binkley, 1993 Trofymow <i>et al.</i> , 1995
k_{lftit_fagr}	0.28 year ⁻¹	<i>Fagus grandifolia</i> leaf litter	Meentemeyer, 1978 Aber <i>et al.</i> , 1980 Stump and Binkley, 1993 Trofymow <i>et al.</i> , 1995
k_{lftit_pist}	0.32 year ⁻¹	<i>Pinus strobus</i> leaf litter	Meentemeyer, 1978 Aber <i>et al.</i> , 1980 Stump and Binkley, 1993 Trofymow <i>et al.</i> , 1995
k_{lftit_pogr}	0.4 year ⁻¹	<i>Populus grandidentata</i> leaf litter	Gough <i>et al.</i> 2007
k_{lftit_quru}	0.3 year ⁻¹	<i>Quercus rubra</i> leaf litter	Meentemeyer, 1978 Aber <i>et al.</i> , 1980 Stump and Binkley, 1993 Trofymow <i>et al.</i> , 1995
k_{rltit}	0.25 year ⁻¹	Root litter (average for <i>Pinus strobus</i> and <i>Acer saccharum</i>)	Aber <i>et al.</i> , 1990
k_{som}	0.1 year ⁻¹	Soil organic matter	Gough <i>et al.</i> , 2007

Model Validation

Model validation and verification are terms to describe a process that was undergone to test the legitimacy of a model. These terms have been defined in various ways by different authors. Porté and Bartelink (2002) distinguish the terms in the following way. Verification is defined as “a qualitative assessment of the consistency of the model outputs when compared with general observations.” Validation is defined as “a quantitative test that directly compares the model outputs to an independent data set.” Using the definitions here, a combination of both methods was used to assess model output.

The first step in model validation was to compare the model predictions to an independent data set. Robert Vande Koppelle provided data from a 1 ha stem map at the Wells site, an unmanaged forest plot at the UMBS surveyed five times between 1974 and 2000. The species and dbh of every stem in the 1 ha plot were recorded during each observation. For model validation, the stem data were grouped according to diameter classes and species to allow comparison to model runs. The initial conditions for MITRIX were set to match the observed stand composition in 1974 and the simulation length was set to 30 years.

Data from managed stands at the Michigan DNR were obtained and analyzed to test the ability of MITRIX to predict dynamics of managed stands. Data were provided by Lawrence Pederson at the Michigan DNR. Fifty-one inventories of stands following Aspen harvests from three Michigan DNR FMUs (Atlanta, Gaylord, and Gladwin) were collected and analyzed. For model validation, an Aspen harvest was simulated and the MITRIX predictions of stand basal area were compared to the observed DNR data.

The next step in model validation was a verification of the ability of MITRIX to predict forest succession. Four 1 ha stem maps from the UMBS created in 2006 and 2007 were used as initial conditions for this verification (Appendix I). All four sites at the UMBS (DIRT Q1, DIRT Q2, FASET A, and FASET B) are dominated by mature Aspen (*Populus grandidentata*), an early successional tree species. For each site, MITRIX was run for 150 years with no management and the change in species composition was observed. MITRIX’s predictions of stand C stock over the model run were then compared to previous results. This step was taken to ensure that the range of predictions was a realistic prediction for a northern temperate forest.

Model Application

MITRIX was used to examine the impacts of management of Aspen dominated stands on C storage, stand present value (PV), and tree species and size diversity. To simulate the status quo Aspen management strategy, MITRIX was programmed to harvest the stand on a 50 year rotation period leaving a small portion of live Aspen stems to stimulate regeneration. The simulation length was set to 200 years.

Management Scenarios

Three alternative management scenarios were modeled: changing rotation period, conversion to a new cover type, and changing the landscape level management strategy. All scenarios were compared to the default Aspen management strategy. Data from one site at the UMBS (DIRT Q1) were used to as initial conditions for the model application. For all scenarios except conversion to a new cover type, the initial harvest was assumed to occur in the first year of the simulation.

The first scenario that was modeled was changing the rotation period of the Aspen harvest. Changing the harvest rotation period has been shown to have important implications for forest C storage (Liski, 2001; Seely et al., 2002). To observe the impacts of altering the rotation period, MITRIX was programmed to simulate rotation periods of 30 years, 60 years, and 90 years; the effects on stand C stock and diversity were assessed.

The next scenario modeled was allowing succession to another forest type. This was achieved through eliminating the periodic clearcutting of the stand. This elimination prohibits the survival of young early successional species such as Aspen and thus, barring a disturbance event, prevents the regeneration of Aspen stands. The majority of Aspen dominated stands in Michigan have a Northern Hardwood understory and the UMBS site that dictated the initial conditions is representative of this larger scale observation. Given this, a conversion to a Northern Hardwood dominated forest type was expected. The Northern Hardwood species represented in MITRIX are: *A. rubrum*, *A. saccharum*, and *F. grandifolia*. Three sub-strategies were explored: conversion with no management, conversion with select cutting, and conversion with a delayed hardwood harvest. Conversion with select cutting involved managing the stand as if it were a Northern Hardwood dominated stand, which was simulated by selectively cutting

20% of the mature Northern Hardwood stems on a 20 year rotation period. This management strategy is in line with the current strategy of Michigan DNR managed Northern Hardwood stands.

The final alternative strategy that was modeled was changing the management strategy to a landscape successional mosaic in order to create and maintain a constant supply of timber leading to a sustainable Aspen harvest as suggested in the 2008 State Forest Management Plan (Michigan Department of Natural Resources, 2008). In this strategy, 20% of all Aspen stands across a compartment or FMU would be harvested in each 10 year inventory period. To model this scenario, MITRIX was run 5 times with a 50-year rotation period Aspen management strategy. The year of the initial harvest was set to years 1, 11, 21, 31, and 41 and the average of the 5 simulation runs was analyzed. Because MITRIX is not spatially explicit, the results of this simulation represent the average stand state of a larger managed area.

Diversity

In order to assess management impacts on stand diversity, a diversity index was calculated for each time step and the average diversity was compared for the various management scenarios. Shannon's Diversity Index is commonly used in a wide variety of ecological applications. The index is calculated from Equation (13).

$$H' = - \sum_{i=1}^m \sum_{j=1}^n p_{ij} \ln p_{ij} \tag{13}$$

In Equation (13), n is the number of size classes; m is the number of species; and p_{ij} is the percentage of stems of species i in size class j relative to the total number of stems. Because the maximum index value will change based on the number of categories, an evenness index was used, which gives a relative diversity. A perfectly equal distribution of stems among species and size classes would yield an evenness index (J') of 1. This index is based on the relationship between the calculated index and the maximum possible index in Equation (14).

$$J' = \frac{H'}{H'_{MAX}}$$

$$H'_{MAX} = -\ln(n * m)$$
(14)

Economics

In order to assess tradeoffs between C storage and timber profits, the present value of the stand was calculated by Equation (15).

$$PV = \sum_{t=1}^n \frac{FV_t}{(1 + dr)^t}$$
(15)

In Equation (15), PV is the present value of the stand, FV_t is the profit from a timber sale at time t , dr is the discount rate, and t is the time into the future (years) that the sale takes place. For simplicity, the profits from timber harvest were assumed to be the only input to stand value. Timber value was estimated based on average price paid per volume of wood from DNR sales between 1992 and 2005; values differed among species and diameter classes (Table 6). Values were rounded to the nearest half dollar for analysis. Because the DNR does not perform the actual harvest, the costs of harvest were assumed to be absorbed into the sale price. Adding a harvest cost would effectively decrease the estimated stand present value. Additionally, adding non harvest value (e.g. recreation, wildlife habitat or C storage) could increase the estimated present value of a stand that is not managed for timber. These non-timber values were not included in the analysis.

The net C impact was calculated by taking the difference between net C change in each management scenario and the reference case. For each modeled scenario, the difference between the C stock and the reference case for each year was summed across the simulation period. This value was used in combination with stand PV to determine the value needed for a Mg of C for the management scenarios that optimized C to offset the economic losses from missed timber revenue.

Table 6. Mean sale values per volume of merchantable timber for species included in MITRIX (USD m⁻³). Values represent mean advertised sale value for all Michigan DNR timber sales from 1992-2005 that occurred in the Atlanta, Gaylord, and Gladwin compartments. The standard deviation appears in parenthesis after the mean. n is the number of sales for each species and size class. Species as defined by the DNR are followed by the corresponding species included in MITRIX.

	Aspen (<i>Populus grandidentata</i> , <i>P. tremuloides</i>)	Birch (<i>Betula papyrifera</i>)	Oak (<i>Quercus rubra</i>)	White Pine (<i>Pinus strobus</i>)	Northern Hardwood (<i>Acer rubrum</i> , <i>A.</i> <i>saccharum</i> , <i>Fagus</i> <i>grandifolia</i>)
Pole (<20 cm dbh)	\$5.53 (1.97) n=767	\$5.89 (1.34) n=10	\$4.93 (2.58) n=146	\$8.20 (1.66) n=6	\$4.60 (2.58) n=146
Sawlog (20+ cm dbh)	\$5.94 (1.93) n=155	\$5.89* n=0	\$7.13 (2.30) n=99	\$7.79 (2.15) n=17	\$7.95 (3.51) n=116

*No sale data for Birch sawlogs were available so the value for poles was used.

The effects of altering the discount rate and altering the timeframe of analysis on optimal management strategies were assessed. Discounting is a way to account for the opportunity cost associated with waiting for future profits, assuming that an investment could have been made elsewhere and earned interest. Given equal sale prices; when a discount rate is used, a timber sale far into the future has a lower PV than a timber sale today. Increasing the discount rate results in a decrease in the PV of all future sales. Two discount rates were used in the analysis: 0.04 and 0.02. A discount rate of 0.04 is close to the rates used in similar applications (e.g. Lin *et al.*, 1996; Krcmar *et al.*, 2005; Spring *et al.*, 2005; Neilson *et al.*, 2006). A discount rate of 0.02 was used to simulate a social discount rate (e.g. Hoen and Solberg, 1994; Seidl *et al.*, 2007), which represents a scenario where something is assumed to be more valuable in the future than a typical commodity. The impacts of a zero discount rate were also assessed.

In order to evaluate the possible effects of changing the time frame of analysis on the optimal management strategy, four time periods of analysis were compared: 10, 50, 100, and 200 years. The effects of changing the time frame of analysis on estimated present value and net C impact were assessed and the optimal management strategy for each time frame was calculated.

RESULTS

Model Validation

Validation: Comparison to Observed Data

Unmanaged stands

MITRIX successfully captured overall trends in basal area (Figure 3) and stem density (Figure 4) for the entire stand and the three dominant tree species, *Populus grandidentata*, *Acer rubrum*, and *A. saccharum* at the unmanaged Wells site at the UMBS. These three species made up more than 90% of the total stand basal area in 1974. In line with the observed data, MITRIX predicted an increase in the basal area of the total stand, as well as the basal areas of *A. rubrum* and *A. saccharum* over the 30 year model run (Figure 3). MITRIX predicted a decrease in *P. grandidentata* basal area, though this predicted decrease was earlier than was observed at the unmanaged site (Figure 3). While the smaller variations in stem densities between years were not captured, the overall trends of increasing total stand stem density and stem densities of *A. rubrum* and *A. saccharum* and decreasing stem density for *P. grandidentata* were successfully predicted by MITRIX (Figure 4).

While the trends were successfully predicted, the majority of basal area and stem density predictions were slightly lower than those observed at the Well's site at the UMBS. Two things could account for this observation. First, site-to-site variability in basal area growth is expected. Second, the UMBS property is located in a section of Michigan with a relatively long growing season compared to the rest of the state, while MITRIX was parameterized to match average conditions across the state (Barnes and Wagner, 2004).

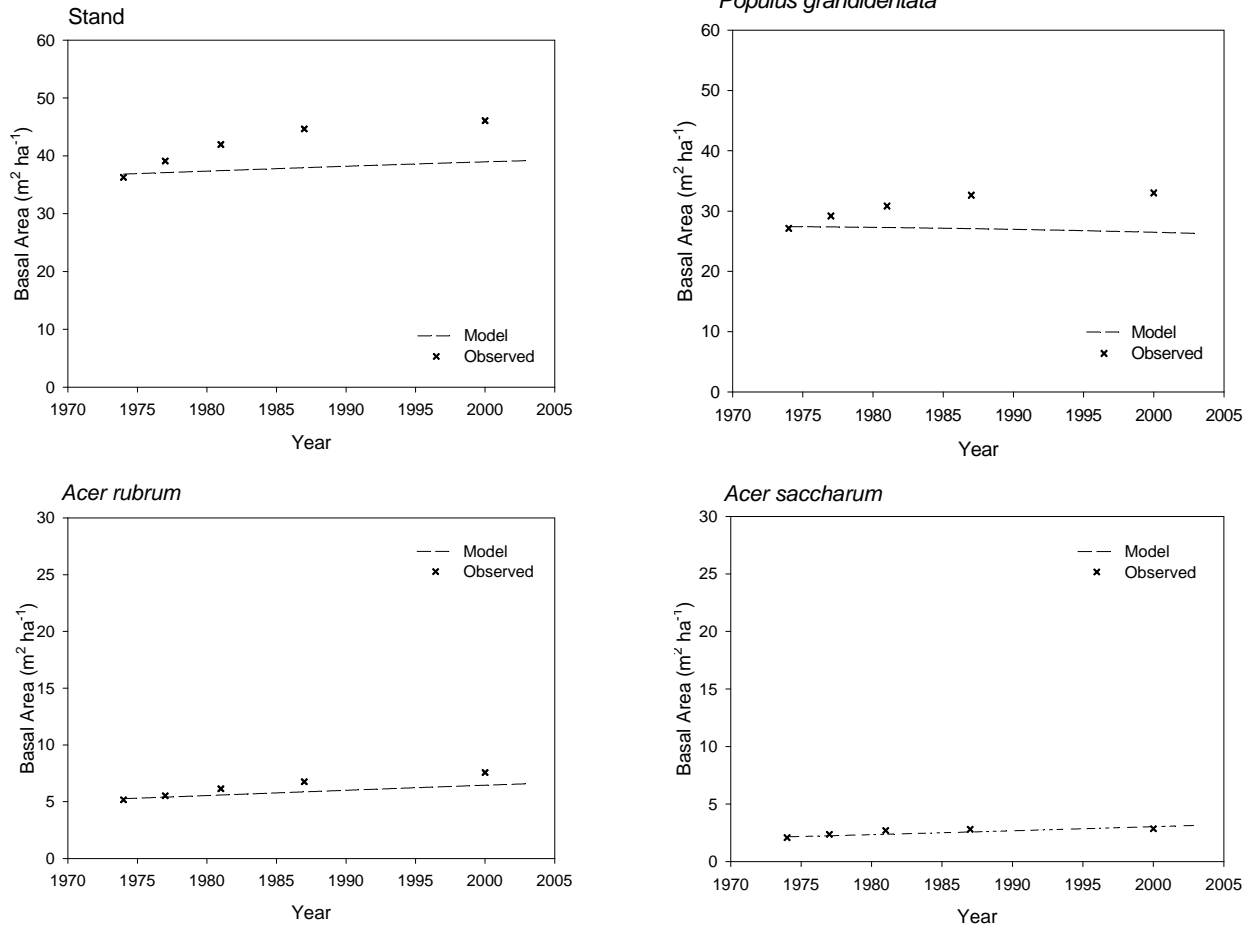


Figure 3. Comparison of results from a MITRIX model run to the observed basal area over a 30 year simulation. Observed data are from the Wells plot at the UMBS.

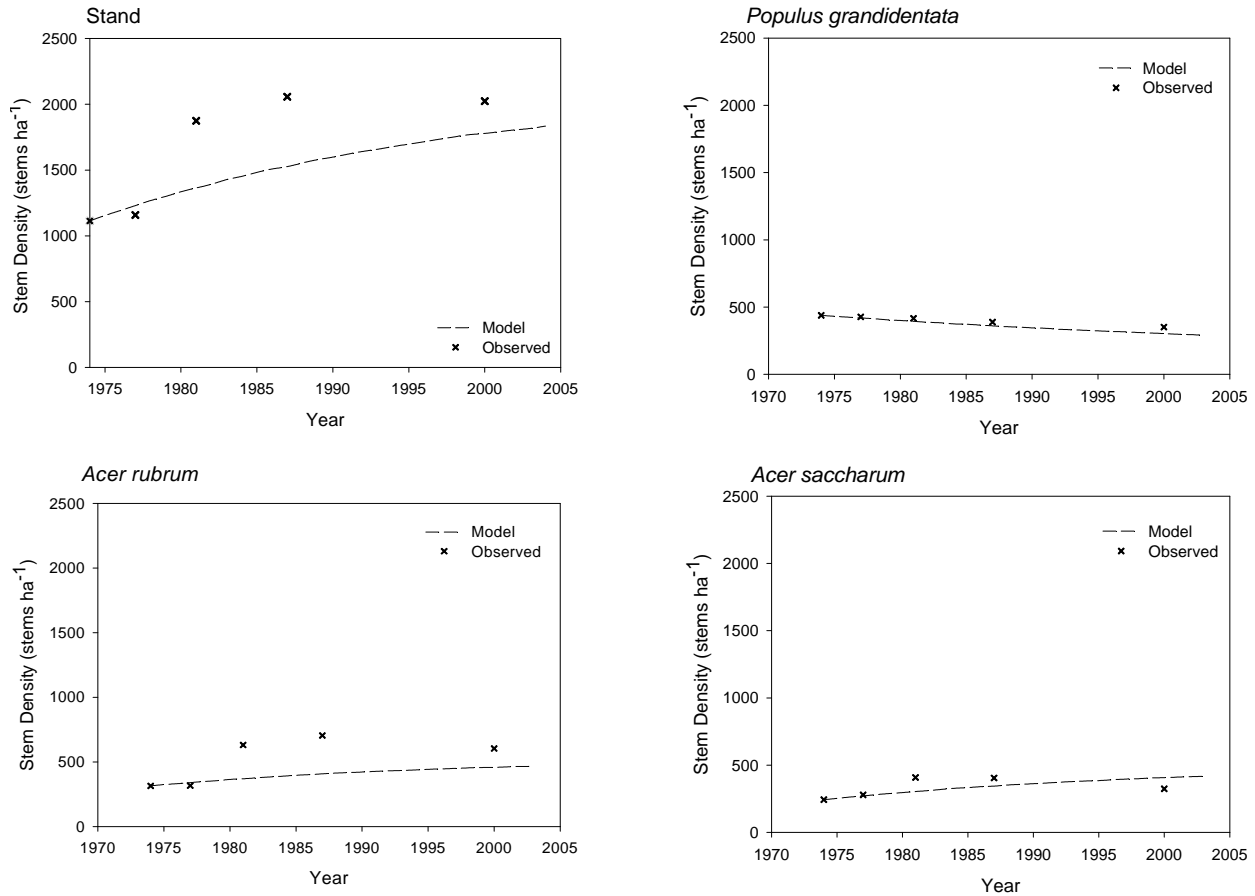


Figure 4. Comparison of results from a MITRIX model run to the observed stem densities over a 30 year simulation. Within each species, stem densities are summed across all size classes. Observed data are from the Wells plot at the UMBS.

Managed Stands

MITRIX successfully captured the trend of increasing basal area in the years following an Aspen harvest in Michigan DNR managed forest stands (Figure 5). A linear regression on DNR inventory data found basal area to be correlated with time since harvest ($R^2=0.48$, $p < 0.001$). The basal area predicted by MITRIX falls almost entirely within the 95% confidence bounds of the DNR inventory data. The slightly high prediction in basal area in later years could be due to differences in method of basal area calculation or to lack of long term DNR data. The DNR records BA measurements rounded to the nearest 10 ft² acre⁻¹ or 2.3 m² ha⁻¹.

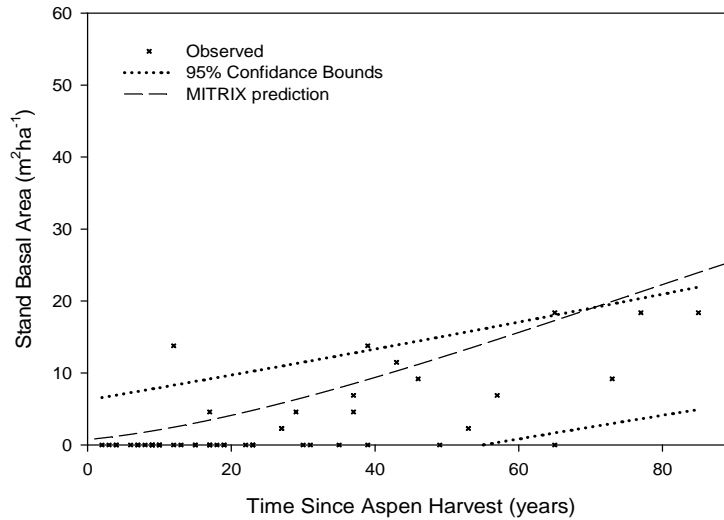


Figure 5. Comparison of results from a MITRIX model run to observations from Aspen stands managed by the Michigan DNR. Observed data correspond to recorded stand basal area following an Aspen harvest. Dotted lines represent the 95% confidence interval.

Verification: Succession

In the absence of prescribed management and assuming no other disturbance, MITRIX predicted that the four mature Aspen sites at the UMBS, indicative of typical forest stands in Northern Michigan, would become dominated by later successional, shade tolerant species within approximately 50-75 years (Figure 6). This supports general observations of forest stand evolution (Whitney, 1987). Because early successional species such as Aspen do not reproduce in their own shade, barring disturbance, stands will be overtaken by later successional species that are highly shade tolerant and can survive for many years in the understory (Kobe *et al.*, 1995).

Two of the four 1 ha stands at the UMBS, FASET A and FASET B, are in an experimental site where all early successional trees were girdled in the spring of 2008 to examine the consequences of accelerated stand succession. When MITRIX was set to simulate this, the result was an immediate change in the living stand basal area and an accompanying shift in dominance to later successional species, (Figure 7). However, MITRIX predicted that the later successional species will not grow in basal area any faster in the absence of Aspen than they would in the presence of a slowly declining Aspen population (Figure 6 and Figure 7), which could be a weakness of the model.

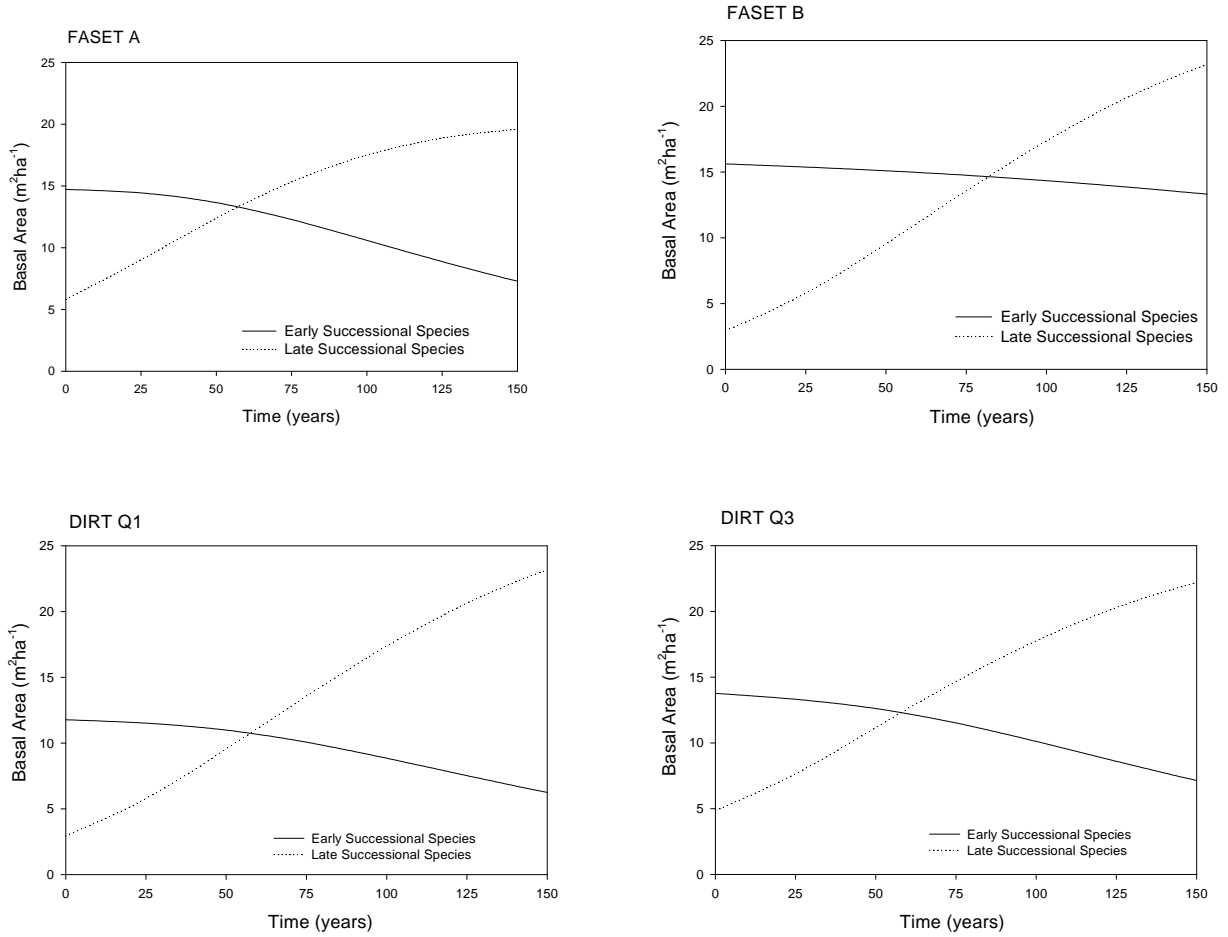


Figure 6. Predicted basal area for early and late successional species in four stands at the UMBS assuming no management or other disturbance. Time 0 corresponds to the year 2007.

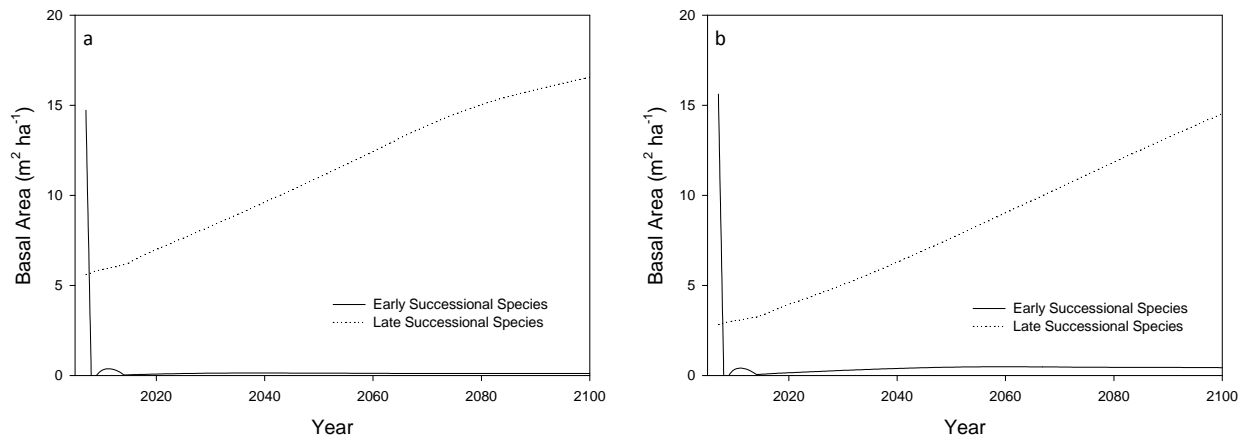


Figure 7. Predicted basal area for early and late successional species in two stands at the UMBS in an experimental accelerated succession site: (a) FASET A and (b) FASET B.

Verification : Carbon Dynamics

The initial C stock for the four 90 year old UMBS stands ranged from 120-150 Mg ha⁻¹. In the absence of prescribed management and assuming no other disturbance, the predicted C stock for the four UMBS stands ranged from 120-280 Mg ha⁻¹ over a 200 year simulation run (Figure 8). The C stock includes C in above and belowground biomass, litter, CWD, and the organic soil layer (Figure 2). The four 1 ha stands at the UMBS were assumed to represent typical stands in Northern Michigan forests. A review of forest C studies by Pregitzer and Euskirchen (2004) found the average C stock (including living biomass, CWD, and the organic soil horizons) in 70-120 year old temperate forests to be approximately 200 Mg ha⁻¹. The review also found an overall trend of an increasing C stock with stand age. MITRIX successfully captured the increasing C stock with stand age and the range in C stock is close to that found in studies of similar forests (Figure 8). Additional verification was obtained from considering the results of a field based study at a nearby site at the UMBS, which estimated the C stock (including above and belowground biomass, leaf litter, root litter, CWD, and the soil O-horizon) in a 60 year old forest stand to be approximately 95 Mg ha⁻¹ (Gough *et al.*, 2007a). This estimate is slightly lower than the MITRIX estimates for the 90 year old stands and the difference is approximately equal to the rate of increase predicted by MITRIX for a 30 year time period.

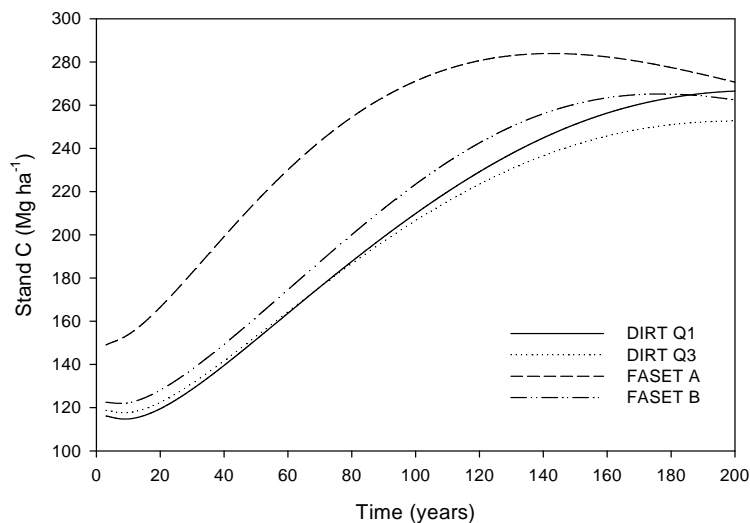


Figure 8. Model prediction of C stock for four 1 ha plots at the UMBS. Time 0 corresponds to 2007, when the stands are 90 year old Aspen dominated. It is assumed that no management or other disturbance occurs over the time of the simulation.

Model Application

Reference Case: Aspen 50 year rotation period

Beginning with the initial composition of the DIRT Q1 plot, with the currently prescribed Aspen management strategy, MITRIX predicted a sharp drop in stand C stock following the initial harvest in year 1 from 120 Mg ha⁻¹ to 50 Mg ha⁻¹ (Figure 9). Subsequently, the C stock in the stand continued to decrease slightly for a few years before beginning to increase again until the next harvest in 50 years. This pattern continued, with each harvest resulting in a sharp decline in stand C storage followed by a gradual increase as the stand recovered. The C stock never reached the initial level of the 90 year old stand.

In examining the species specific stem densities and basal areas, the stem density of the later successional species *A. rubrum* increased throughout the 50 year growth period (Figure 10a), but the stand basal area continued to be dominated by Aspen (*P. grandidentata*) throughout the simulation run (Figure 10b). Diversity followed a similar trajectory as C storage in this management scenario, but the shape of the increase was different (Figure 11). After the immediate decline in diversity following a harvest, diversity increased sharply within a few years and then continued to increase at a slower rate.

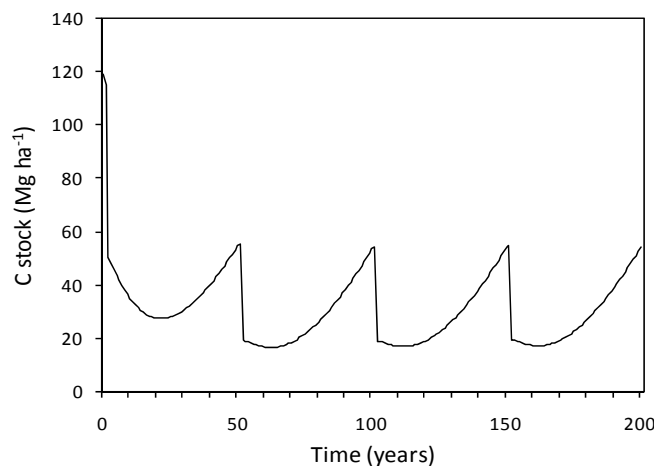


Figure 9. Simulated C stock dynamics for a stand managed for Aspen. The rotation period of 50 years was selected to match that used by the Michigan DNR. All C pools included in the conceptual model were summed. Mineral soil was not included in the analysis. Initial forest state was set to match an existing stand at the UMBS.

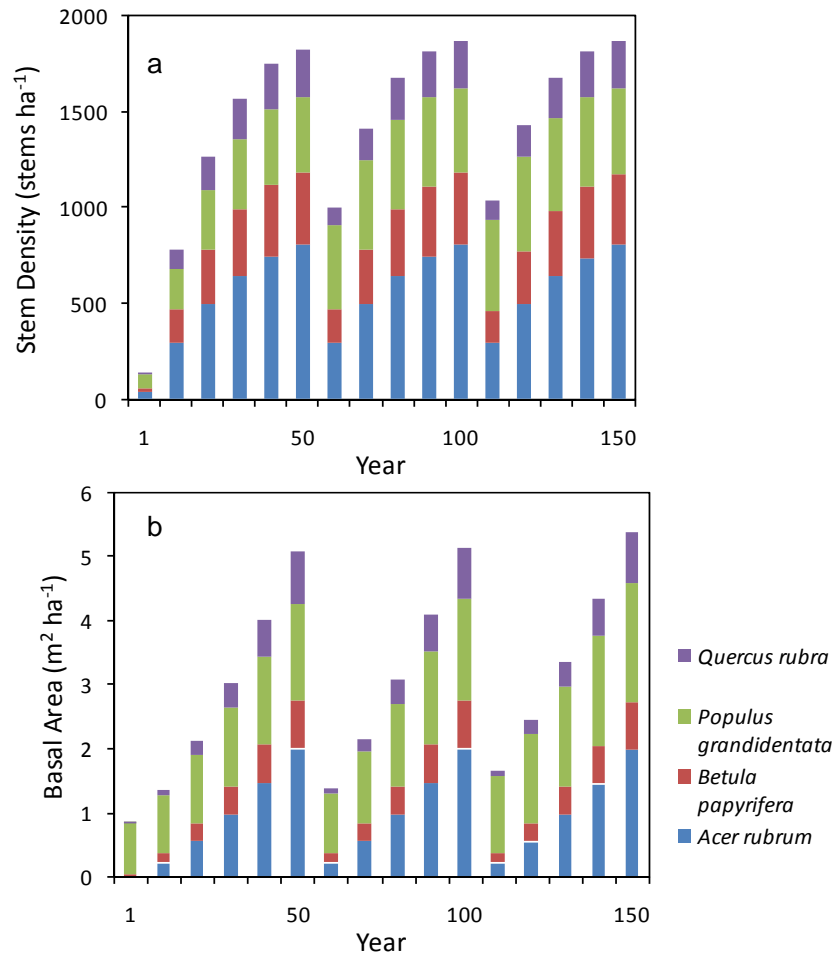


Figure 10. Simulated species specific (a) stem density and (b) basal area for the reference case: maintaining Aspen with a 50 year rotation period. The four dominant species are shown.

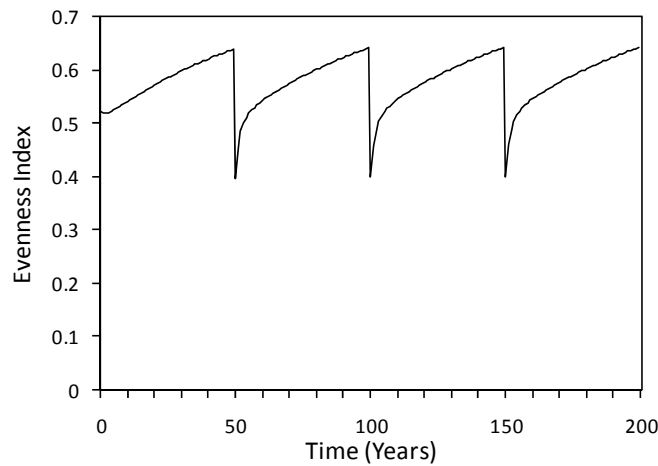


Figure 11. Simulated changes in diversity through time for a stand managed for Aspen with a 50 year rotation period. Initial forest state was set to match an existing stand and the UMBS. Diversity here is quantified as an evenness index (J') as defined in Equation (14).

Scenario 1: Maintain Aspen with changing rotation period

When the rotation period was decreased to 30 years, the trajectory of C stock was similar to that of the reference case, but lower maximum and minimum C stocks were reached (Figure 12). Increasing the rotation period to either 60 or 90 years, resulted in a larger C stock overall corresponding to a larger increase in biomass accumulation between harvests (Figure 13). The peak in C stock for the 90 year rotation period scenario reached approximately the same level as the initial C stock of the 90 year old Aspen stands and the trough did not reach as low of a level as in the reference case (Figure 13).

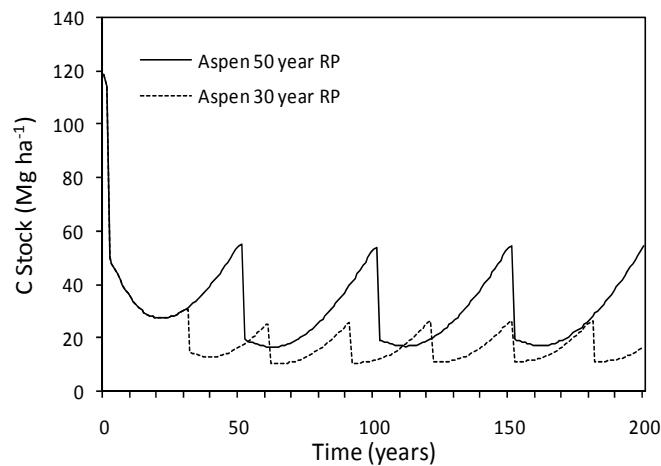


Figure 12. Effect of decreasing the rotation period (RP) on C stock in a forest stand. A 30 year rotation period was modeled and compared to the current 50 year rotation period management scenario. All C pools included in the conceptual model were summed. Mineral soil was not included in the analysis. Initial forest state was set to match an existing stand at the UMBS.

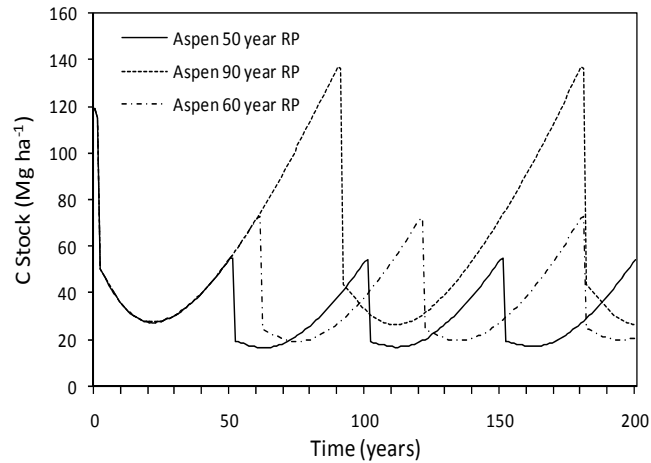


Figure 13. Effect of increasing rotation period (RP) on C stock over a 200 year simulation period. Rotation periods of 60 and 90 years were modeled and compared to the current 50 year rotation period strategy. All C pools included in the conceptual model were summed. Mineral soil was not included in the analysis. Initial forest state was set to match an existing stand at the UMBS.

When the rotation period was shortened to 30 years, the stand never reached the same level of diversity as in the reference case (Figure 14). Similarly, the shorter rotation period resulted in a lower overall stand basal area compared to the reference case, though *P. grandidentata* continued to dominate the stand throughout the simulation period (Figure 15).

Increasing the rotation period had the opposite effect on diversity (Figure 16). As the rotation period was lengthened to 60 and 90 years, the peaks in diversity increased slightly and the dips in diversity were slightly less than the reference case following the harvest. The species specific stem densities and basal areas for the 60 year rotation period showed similar dynamics to the reference case (Figure 17a&c). In the 90 year rotation scenario, the stand has already begun to succeed to a Northern Hardwood forest as evidenced by the relative increase in *A. rubrum* basal area compared to *P. grandidentata* at the time of the subsequent harvest (Figure 17d). The stem density of early successional species had also begun to decline by the time of the subsequent harvest (Figure 17b).

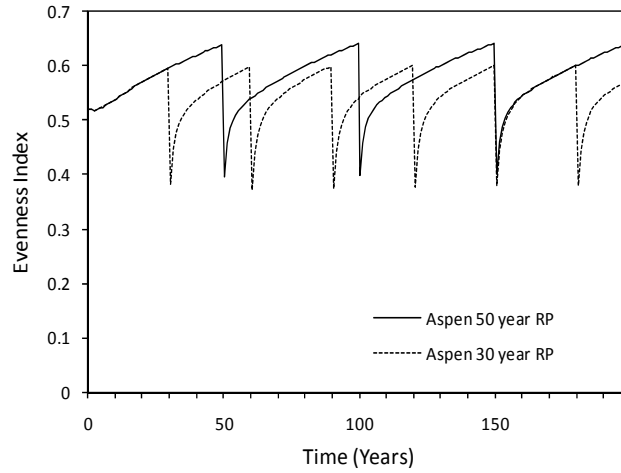


Figure 14. Effects of decreasing rotation period (RP) on stand diversity. Diversity is calculated as an evenness index as in Equation (14).

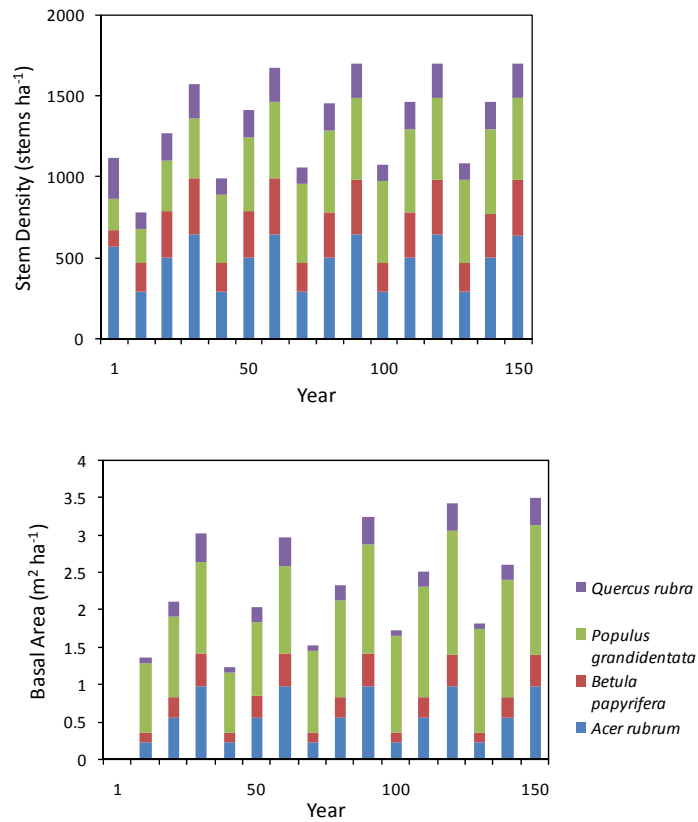


Figure 15. Species specific stem density and basal area for maintaining Aspen with a decreased rotation period of 30 years. The four dominant species are shown.

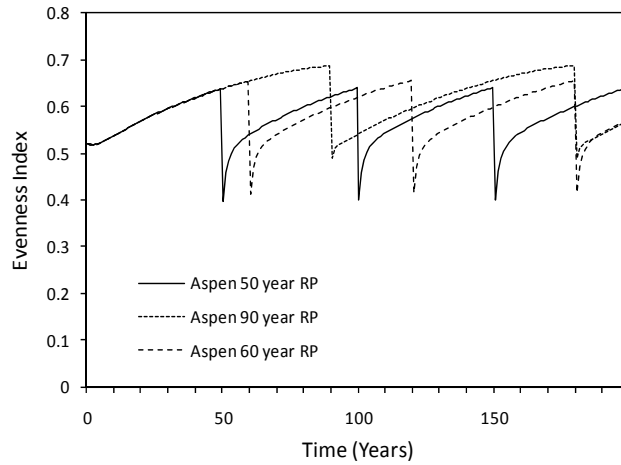


Figure 16. Effects of increasing rotation period (RP) on stand diversity. Diversity is calculated as an evenness index as in Equation (14).

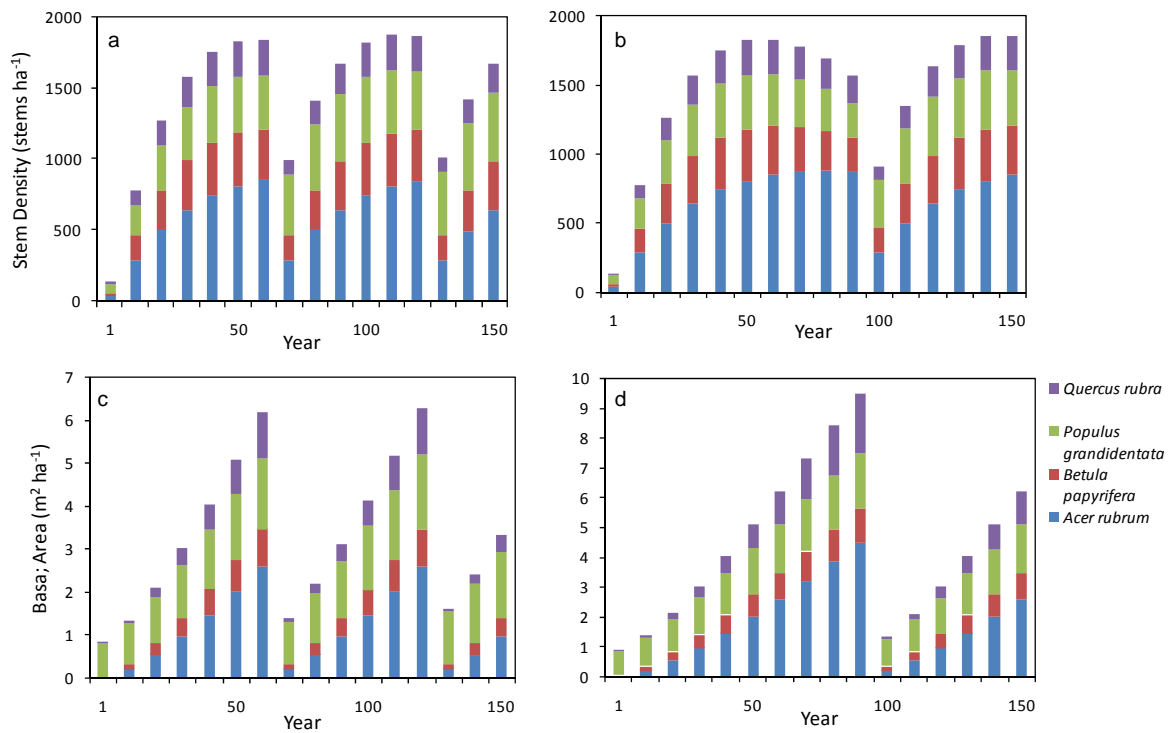


Figure 17. Species specific stem density and basal area for maintaining Aspen with increasing rotation periods. (a) and (c) correspond to a 60 year rotation period; (b) and (d) correspond to a 90 year rotation period. The four dominant species are shown.

Scenario 2: Allowing succession

When the forest was allowed to succeed to a different cover type, with no prescribed management, the C stock in the forest stand increased over the simulation leveling out at around 250 Mg C ha⁻¹ (Figure 18). With select cutting of Northern Hardwood trees on a 20 year rotation period, a similar initial increase in stand C stock was observed, but the stock leveled out at a lower level of approximately 220 Mg C ha⁻¹ (Figure 18). Both strategies resulted in a large increase in stand C stock in comparison to the Aspen maintenance scenarios.

Regardless of management, allowing succession resulted in higher and less variable diversity indices compared to the Aspen maintenance strategies (Figure 19). With no management, there was an increase in stem densities of later successional species (*A. rubrum*, *F. grandifolia*) over time accompanied by a decrease in stem densities of the other three major species (*P. grandidentata*, *B. papyrifera*, and *Q. rubra*) (Figure 20a). The basal area of *P. grandidentata* decreased over time, while the basal area of *Q. rubra* increased and leveled off and the basal area of the later successional species increased continually through the simulation run (Figure 20c). A similar pattern is observed when selective cutting of Hardwoods was allowed, but the basal area and stem densities of these species (*A. rubrum*, *F. grandifolia*) remained lower throughout the length of the simulation (Figure 20b&d).

An additional strategy of delayed Hardwood harvest - allowing succession and harvesting the high valued, later successional tree species in after 100 years - did not alter the specific stand dynamics through time and was not analyzed individually. This scenario was included in the comparative analysis in the subsequent section.

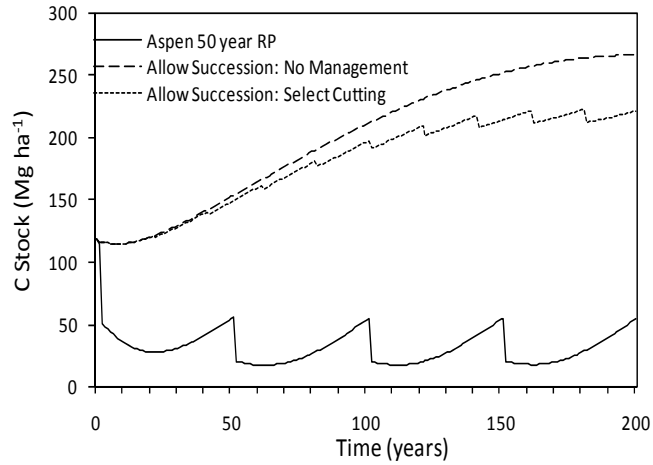


Figure 18. Effect of allowing succession on stand C stock versus maintaining an Aspen dominated stand with a 50 year rotation period (RP). The effect of maintaining a Hardwood dominated forest with selective cutting is also modeled. All C pools included in the conceptual model were summed. Mineral soil was not included in the analysis. Initial forest state was set to match an existing stand at the UMBS.

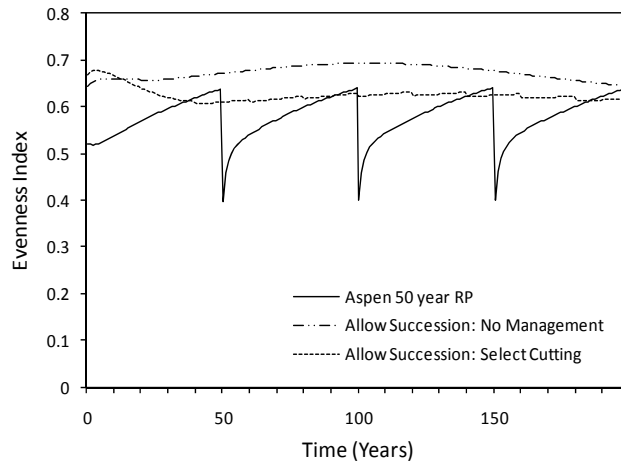


Figure 19. Effect of allowing succession to a Hardwood dominated stand on stand diversity versus the current management strategy of maintaining an Aspen dominated stand with a 50 year rotation period (RP). Diversity is calculated as an evenness index as in Equation (14).

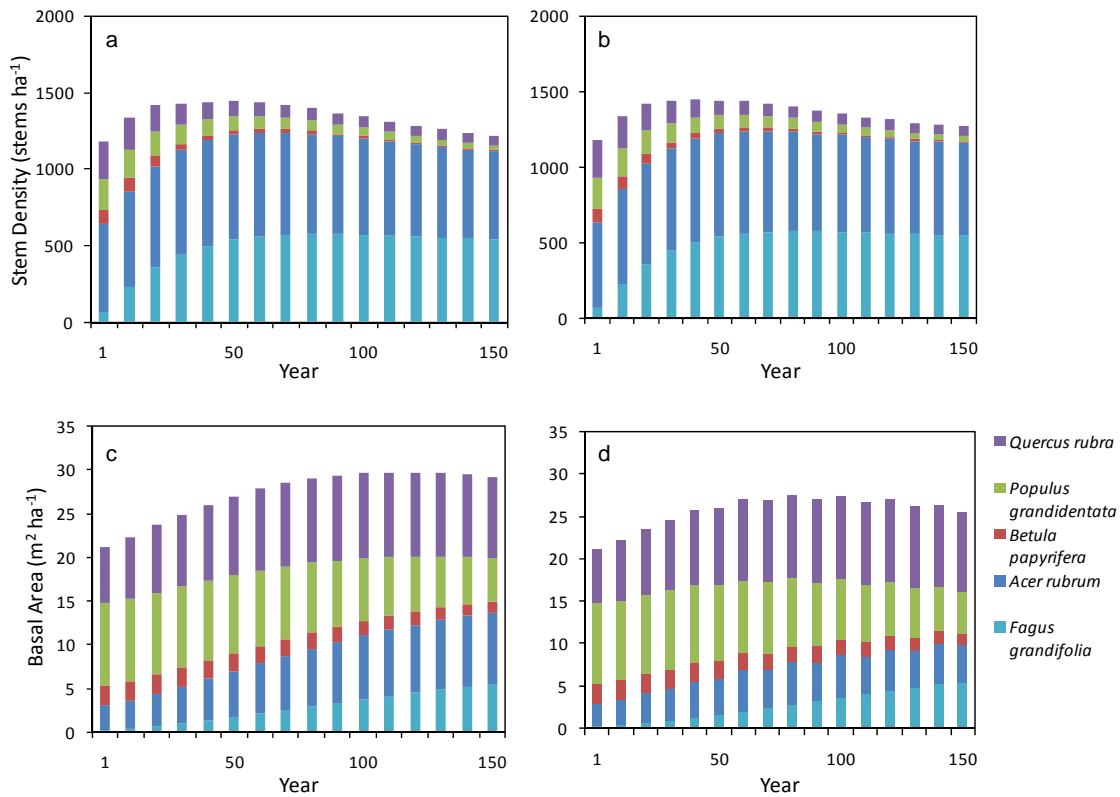


Figure 20. Species specific (a-b) stem density and (c-d) basal area for allowing succession. (a) and (c) correspond to a scenario of no management; (b) and (d) correspond to a scenario of selectively cutting Hardwoods on a 20 year rotation period. The five dominant species are shown.

Accelerated Succession

In a scenario where all early successional trees (*P. grandidentata* and *B. papyrifera*) were girdled to artificially accelerate succession, as occurred in two of the sites at the UMBS in early 2008, the C dynamics through time were altered (Figure 21). At both sites, there was an initial decrease in C stock immediately following the girdling followed by a slow increase, but the dynamics at the individual sites were different. In FASET A, the C stock leveled out later than the no management scenario, but reached approximately the same level (Figure 21a). In FASET B, the C stock leveled out slightly later but at an increased level compared to the no management scenario (Figure 21b). Also, the rate of C uptake increased at this site.

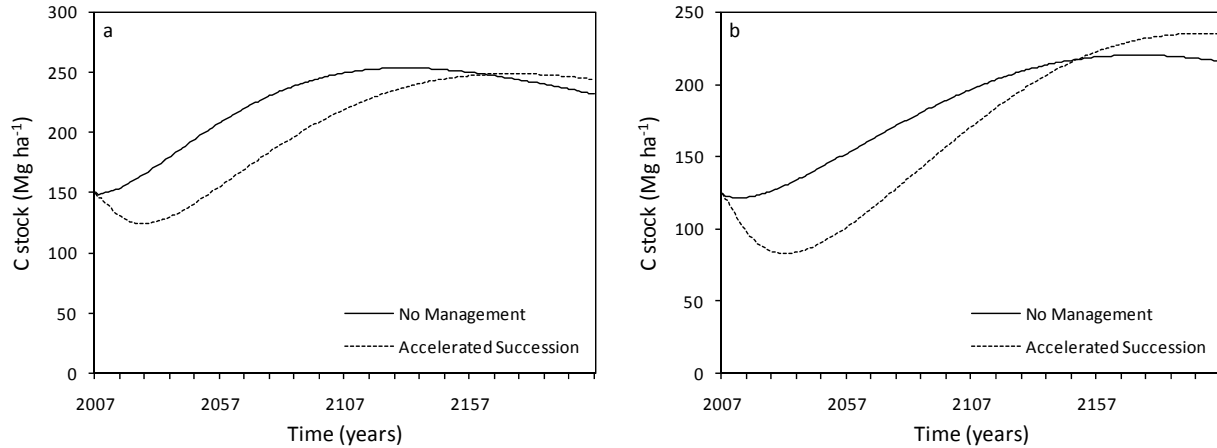


Figure 21. Predicted C stock through time when succession is artificially accelerated via the girdling of all early successional trees in 2008 versus relative to no management at two sites at the UMBS: (a) FASET A and (b) FASET B.

Scenario 3: Changing management strategy

When a landscape perspective was taken in the management of Aspen, the results represent the composition of the average stand across a larger landscape. The result of the landscape successional mosaic management strategy was higher troughs and lower peaks in the stand C stock and less variation in C stock through time relative to the reference case (Figure 22).

The effect of the landscape successional mosaic on stand diversity was similar to the effect on C stock (Figure 23). When a landscape level perspective was taken, there was less variation in the diversity of stands through time compared to the reference scenario and the dramatic dips in diversity were eliminated. The species specific stem density and basal area illustrate this stabilization of the average stand across a region (Figure 24).

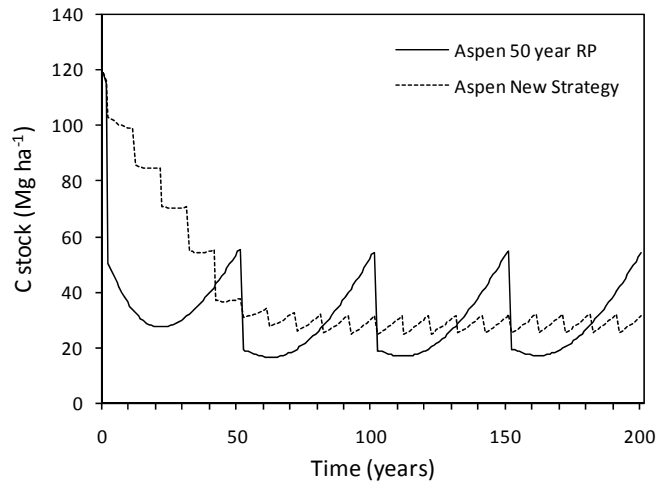


Figure 22. Simulated C stock of a forest stand managed for Aspen with current strategy of clearcut with 50 year rotation period and landscape successional mosaic strategy where 20% of Aspen stands are cut every 10 years on a 50 year rotation period. All C pools included in the conceptual model were summed. Mineral soil was not included in the analysis. Initial forest state was set to match an existing stand at the UMBS.

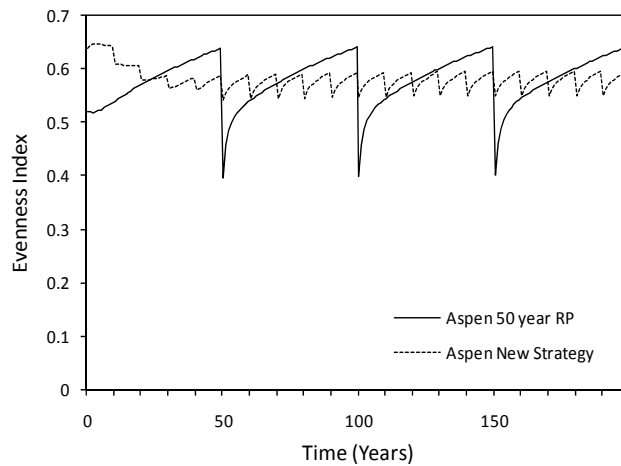


Figure 23. Simulated effect of changing management strategy on stand diversity. The proposed landscape successional mosaic strategy consists of harvesting 20% of Aspen stands every 10 years on a 50 year rotation period. Diversity is measured as an evenness index as in Equation (14).

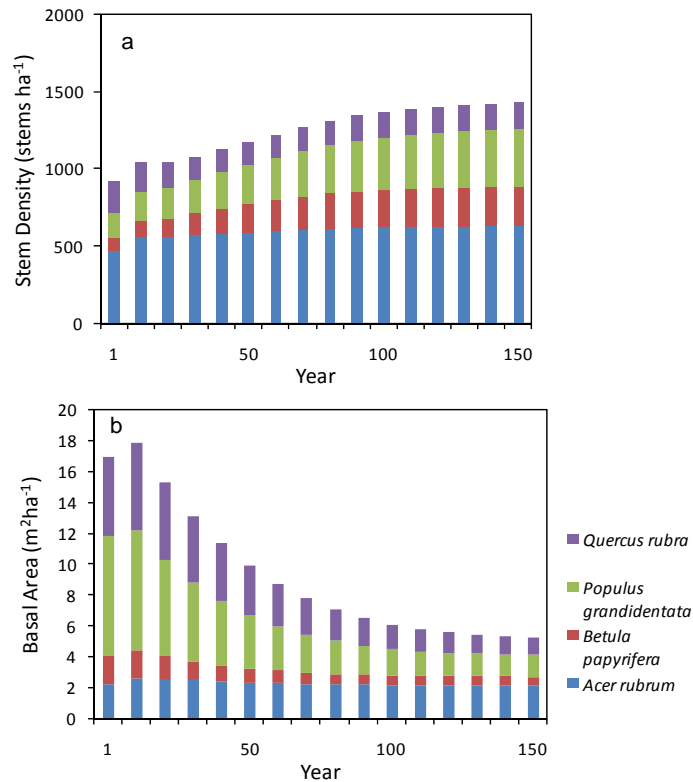


Figure 24. Simulated landscape-scale species specific (a) stem density and (b) basal area for the landscape successional mosaic Aspen management scenario: harvesting 20% of Aspen stands every 10 years on a 50 year rotation. The four dominant species are shown.

Carbon Storage and Species Diversity

The management scenarios simulated resulted in different dynamics of stand C stock over time. To observe the net effects of each scenario on forest C stock, the deviations in net C over the 200 year simulation runs from the baseline current Aspen management strategy for each scenario were compared (Table 7). The net C impact represents the difference in C stock summed across all years in the simulation. Maximum net C impact corresponded to the scenarios of conversion to a later successional stand cover. Of the sub-strategies, the elimination of management resulted in the greatest net C storage, followed by selectively cutting hardwood trees. The delayed hardwood harvest resulted in a slightly lower net C impact than the other sub-strategies. All alternative Aspen management scenarios resulted in an increase in net stand C stock with the exception of the shortened rotation period scenario. Of the Aspen maintenance scenarios, the landscape successional mosaic strategy resulted in the highest net C gain.

As in the net C impact analysis, the conversion to a later successional cover type with no management resulted in a higher average diversity through the 200 year simulation period (Table 7). This was followed by the landscape successional mosaic Aspen maintenance strategy and the selective cutting of Hardwoods following stand succession. For the Aspen maintenance strategy, there was a positive correlation between length of the rotation period and the average diversity through the simulation period.

Table 7. The net C impact and average diversity for each of the proposed management strategies. Table values represent the deviation in net C stock (Mg C ha⁻¹) compared to the current Aspen maintenance strategy over a 200 year simulation period. All values were rounded to the nearest 100 Mg C ha⁻¹. Diversity is determined by the evenness index in Equation (14).

Management Strategy	Strategy Details	Net C Impact (Mg C ha ⁻¹)	Average Diversity (Evenness Index = J')
Maintain Aspen: Current Management	50 year rotation period	0	0.58
	30 year rotation period	-400	0.55
Maintain Aspen: Change Rotation Period	60 year rotation period	200	0.59
	90 year rotation period	800	0.61
	20% of Aspen stands across landscape harvested every 10 years	2,100	0.64
Maintain Aspen: Change to Landscape Successional Mosaic	Selective cutting of hardwoods on a 20 year rotation period	5,400	0.63
	No Management	5,800	0.68
	Delayed hardwood harvest	5,000	0.57

Stand Present Value and Discount Rates

The choice of discount rate had an impact on the optimal strategy seeking to maximize the present value (PV) of the stand with a 200 year time frame of analysis (Table 8). With a discount rate of 0.04, the four Aspen maintenance scenarios were virtually indistinguishable in PV, while the landscape successional mosaic resulted in a PV estimate of approximately 2/3 that of the other stand-level Aspen management scenarios. The scenarios allowing succession resulted in very little profit. When a lower discount rate of 0.02 was used, the landscape successional mosaic strategy was virtually indistinguishable from the other Aspen scenarios. Regardless of the discount rate chosen, maintaining Aspen resulted in a higher stand PV

compared to the scenarios which allowed succession to another forest type. However, when a discount rate of 0 was used, the Northern Hardwood stands had comparable value.

In sum, while there was little change in the calculated PV in the current management strategy or the altered rotation periods with different discount rate choices, there was a large impact for the other scenarios. The landscape mosaic strategy for Aspen management, the allowed succession with select cutting of Northern Hardwoods, and the delayed hardwood harvest all result in economic activity further into the future making the impact of the chosen discount rate especially significant in evaluating these cases. Because stand PV was based only on revenue from timber harvests, the no management scenario resulted in a zero value for stand PV.

Table 8. Comparison of estimated stand present value (PV) for the different management scenarios with a 200 year time frame of analysis (USD ha⁻¹). The estimates of PV include only profits from timber sales. All values were rounded to the nearest \$100.

Management Strategy	Strategy Details	Discount Rate		
		0.04	0.02	0
Maintain Aspen: Current Management	50 year rotation period	\$128,300	\$137,800	\$183,900
	30 year rotation period	\$127,900	\$134,100	\$161,600
Maintain Aspen: Change Rotation Period	60 year rotation period	\$128,400	\$140,000	\$216,700
	90 year rotation period	\$127,800	\$143,600	\$292,400
	20% of Aspen stands across landscape harvested every 10 years	\$86,400	\$134,000	\$270,500
Maintain Aspen: Change to Landscape Successional Mosaic	Selective cutting of hardwoods on a 20 year rotation period	\$4,800	\$15,800	\$123,000
	No Management	\$0	\$0	\$0
	Delayed hardwood harvest	\$1,400	\$11,500	\$178,300

Time Frame

The choice of time frame of analysis had important implications for the optimal strategy for C storage and PV as well as the estimate of price of C needed to equalize economic losses from forgone timber harvest (Table 9, Table 10, and Table 11). All previous results assumed a time frame of analysis of 200 years. Assuming a discount rate of 0.04 for timber profits, the strategy that maximized C storage over a 200 year time period was conversion to a later successional forest cover and the strategy that maximized stand PV was maintaining Aspen with a rotation

period of 60 years (Table 7 and Table 8). The 60 year rotation period remained optimal for maximizing stand PV with a 100 year time frame of analysis. With a 50 year time frame of analysis, the 30 year rotation strategy results in the highest estimated stand PV because it is the only strategy that includes a second timber sale. With a very short time frame of analysis of 10 years, all Aspen maintaining strategies with the exception of the new landscape level strategy result in an equivalent estimate of stand PV estimate, as future harvests are not considered in the estimate.

Assuming that only timber profits are included in stand PV and assuming a discount rate of 0.04 for timber profits and a discount rate of 0.02 for C, the value of C necessary for the gain in net C to offset the decrease in profits from timber revenue was calculated by dividing the net difference in stand PV by the net difference in C for each scenario relative to the reference scenario (Table 9 and Table 11). Assuming a 200 year time frame of analysis, the price needed for the strategies that maximize C storage to break even with the status quo management is \$22 - 26 per Mg C ha⁻¹. This estimate is affected by both the time frame of analysis and the choice of discount rates.

For net C impact, converting to a later successional forest remains the optimal strategy regardless of timeframe, but the perceived amount of C offset decreases as the time frame of analysis shortens (Table 10). This has important implications for determining the price of C needed to offset the economic losses from lost timber profits. While the scenario of conversion to a later successional forest cover was the optimal C scenario, the timber profits from this scenario were low because, even though the value of the timber for these species is higher than Aspen, the economic activity took place on a longer timeframe and a smaller scale. The price of C needed in each scenario to balance the decreased timber profits decreases with an increasing time frame of analysis (Table 11). With a 200 year time frame of analysis, the price needed for the storage-maximizing C strategies to break even with the status quo management is \$22 - 26 per Mg C ha⁻¹; with a 100 year time frame of analysis the break-even price is \$29 - \$31 per Mg C ha⁻¹; with a 50 year time frame of analysis the break-even price is almost double that of the 200 year time frame estimate. A ten year time frame of analysis yields break-even estimates of C prices to be almost 10 times that of the 200 year time frame of analysis, \$220 per Mg C ha⁻¹.

Table 9. Comparison of estimated stand present value (PV) for the different management scenarios with a different time frames of analysis (USD ha⁻¹). All values were rounded to the nearest \$100. The estimates of PV include only profits from timber sales and assume a discount rate of 0.04.

Management Strategy	Strategy Details	Revenue from Timber Harvest (Stand PV)			
		200 years	100 years	50 years	10 years
Maintain Aspen: Current Management	50 year rotation period	\$128,300	\$131,000	\$127,800	\$127,800
	30 year rotation period	\$127,900	\$130,500	\$130,000	\$127,800
Maintain Aspen: Change Rotation Period	60 year rotation period	\$128,400	\$131,200	\$127,800	\$127,800
	90 year rotation period	\$127,800	\$130,700	\$127,800	\$127,800
Maintain Aspen: Change to Landscape Successional Mosaic	20% of Aspen stands across landscape harvested every 10 years	\$86,400	\$66,000	\$61,000	\$25,600
Manage for Carbon: Convert to Later Successional Forest	Selective cutting of hardwoods on a 20 year rotation period	\$4,800	\$3,900	\$2,800	\$800
	No Management	\$0	\$0	\$0	\$0
	Delayed hardwood harvest	\$1,400	\$1,300	\$0	\$0

Table 10. The net C impact for each of the proposed management strategies with different time frames of analysis. Values represent the deviation in net C stock (Mg C ha⁻¹) compared to the current Aspen maintenance strategy. Positive values correspond to net increases in C stock compared to the current management and negative values correspond to net decreases in C stock compared to the current management. Table values assume a C discount rate of 0.02. All values were rounded to the nearest 100 Mg C ha⁻¹.

Management Strategy	Strategy Details	Net C Impact (Mg C ha ⁻¹)			
		200 years	100 years	50 years	10 years
Maintain Aspen: Current Management	50 year rotation period	0	0	0	0
	30 year rotation period	-400	-300	-200	0
Maintain Aspen: Change Rotation Period	60 year rotation period	200	100	0	0
	90 year rotation period	800	700	0	0
Maintain Aspen: Change to Landscape Successional Mosaic	20% of Aspen stands across landscape harvested every 10 years	2,100	1,900	1,500	500
Manage for Carbon: Convert to Later Successional Forest	Selective cutting of hardwoods on a 20 year rotation period	5,400	4,300	2,700	600
	No Management	5,800	4,500	2,700	600
	Delayed hardwood harvest	5,000	4,200	2,600	600

Table 11. The price of C needed to equalize economic loss from decreased timber profits resulting from altering the current Aspen management strategy. Values are price per ton of C. A 0.04 discount rate is assumed for timber profits and a 0.02 discount rate is assumed for C. Values of N/A indicate a situation where there is a net C loss, and thus a C price would have no impact on any economic loss. Values of * indicate a situation where there is a net gain in PV and/or C storage.

Management Strategy	Strategy Details	Price of C Needed to Equalize Economic Loss			
		200 years	100 years	50 years	10 years
Maintain Aspen: Current Management	50 year rotation period	-	-	-	-
Maintain Aspen: Change Rotation Period	30 year rotation period	N/A	N/A	*	\$0
	60 year rotation period	*	*	\$0	\$0
	90 year rotation period	\$1	\$0	\$0	\$0
Maintain Aspen: Change to Landscape Successional Mosaic	20% of Aspen stands across landscape harvested every 10 years	\$20	\$35	\$46	\$219
Manage for Carbon: Convert to Later Successional Forest	Selective cutting of hardwoods on a 20 year rotation period	\$23	\$29	\$47	\$219
	No Management	\$22	\$29	\$47	\$219
	Delayed hardwood harvest	\$26	\$31	\$49	\$220

DISCUSSION

A model, MITRIX, was developed that allows a user to look at the effects of forest management on C storage, tree species diversity and stand present value (PV). MITRIX was designed to be useful to FMU managers in Michigan, where management decisions are prescribed based on species and size classes and available data are coarse in spatial and temporal scale. MITRIX is exploratory in nature, but nonetheless has the potential to serve as a valuable tool for FMU managers seeking potential effects of incorporating C storage into management prescriptions. Empirical models, such as MITRIX, have been shown to predict as well as process based models that require a great deal of environmental input data (Porte and Bartelink, 2002) and, because of the relatively few inputs needed, MITRIX has the potential to be useful when there is minimal information available about a forest stand.

In allowing the user to input the initial stand composition and dictate which tree species are present in the area, MITRIX is able to make fairly accurate predictions of stand growth for a specific site. Because the parameters are dependent on the initial state, MITRIX predictions are more accurate when more detailed knowledge is available about the initial stand composition. In addition, it may be less reliable for predictions far into the future. At the same time, given that MITRIX is not spatially explicit and the results represent the average state of a given scale with all attributes normalized by area, a stand level analysis can easily, but not directly, be scaled up to a landscape level.

This research used a scenario analysis to assess the impact of several alternative management scenarios on C storage, stand composition, stand diversity, and stand PV. This method was similar to methods applied in previous studies (e.g. Liski, 2001; Garcia-Gonzalo *et al.*, 2007; Seidl *et al.*, 2007). Optimization or goal programming have been used in other research to identify optimal strategies for meeting diverse management goals (e.g. Backeus *et al.*, 2005; Krcmar *et al.*, 2005; Huang and Kronrad, 2006; Neilson *et al.*, 2006), but this type of analysis requires assigning relative values to each component of the analysis. In multi-use management the value of the various components may differ among locations and thus a scenario analysis allows the model user to decide what components to assign the greater value to.

Effect of Management on C

Overall, the simulation results suggest that including C storage in forest management decisions in Michigan favors moving away from Aspen maintenance and allowing succession of stands. For a given Aspen dominated stand, allowing succession of the stand results in the greatest gain in forest C stock through time (Figure 18, Table 10). All sub-strategies that allow succession of the forest stand result in a higher net gain in C stock compared to the Aspen maintenance scenarios, though shifting management to selective cutting or delayed harvest of the later successional Hardwoods, results in only a slightly lower maximum C stock than an unmanaged forest. These results imply that any stand level management strategy that considers C storage will favor later successional species and that converting to a later successional forest type is the optimal strategy for maximizing stand C storage. Later successional trees such as *A. rubrum*, *A. saccharum*, and *F. grandifolia* tend to live longer, grow larger, and support a denser understory than early successional tree species such as *P. grandidentata* and *B. papyrifera* (Barnes and Wagner, 2004). Therefore, if the goal is to increase the C stock of a forest stand, maintenance of Aspen dominated forests is not the optimal management strategy.

If an Aspen stand is to be maintained, the simulated results suggest that increasing the rotation period has a positive effect on biomass accumulation, which increases total C stock over time. Previous studies have found that increasing rotation periods leads to increases in C in living biomass (Liski, 2001; Seely *et al.*, 2002) as well as litter and total ecosystem C (Seely *et al.*, 2002). In the present analysis a 90 year rotation period resulted in the greatest net gain in C stock, followed by a 60 year rotation period. These results also suggest that the C stock in the forest stand continues to accumulate for at least 90 years following an Aspen harvest.

Decreasing the rotation period to 30 years had a negative impact on net C stock. While shorter rotation periods have been shown to increase the C inputs to the forest floor, the model results suggest that this is overwhelmed by aboveground biomass growth. The type of harvest can impact the C dynamics at the surface soil layers due to differences in disturbance of the forest floor among methods (Yanai *et al.*, 2003). While MITRIX does include inputs to these soil levels, it does not allow for comparisons of different harvest types or intensity. Including options for variation of input based on harvest type could impact the results of the present

analysis, though if the methods do not change the amount of wood actually harvested, the impact is likely to be small.

The present study is limited to changes in C in the living biomass, CWD, litter, and organic soil horizons. The soil C dynamics are simplified and the mineral soil layer is not considered in the analysis. The C stock in temperate forests can represent a large percentage of the total C stock and is commonly estimated at about 60% (Birdsey *et al.*, 1993; Post *et al.*, 2001; Currie *et al.*, 2003). The actual amount of carbon stored in soil is dependent on both soil type and the amount of soil organic matter present (Liski *et al.*, 2002). The high variability in soil C content in forest ecosystems makes it difficult to quantify this pool in the absence of field measurements. While including the mineral soil in the analysis could increase total C stock estimates by 40 to 120 Mg ha⁻¹ (Pregitzer and Euskirchen, 2004), several studies have found the mineral soil to be mainly unaffected by forest harvest (e.g. Seely *et al.*, 2002) implying that the decision not to include this pool would have little impact on the comparison of scenarios in the present analysis. Additionally, other studies have shown that increased productivity in older forests can lead to increases in mineral soil C (Jandl *et al.*, 2007), which would only lend support to the findings of this analysis. Improved predictions of soil C would require on site measurements of soil C stock and variability.

Scaling up to the Landscape Level

The results of the reference case and the altered rotation period scenarios scaled up to a regional or landscape level are representative of the “boom and bust” strategy currently employed by the Michigan DNR: a large amount of Aspen harvests occur within a short time of each other resulting in a preponderance of similarly aged Aspen forests across the state managed with the same rotation period (Michigan Department of Natural Resources, 2008). The landscape successional mosaic strategy for Aspen dominated stands would result in 20% of the Aspen stands across a region or landscape being harvested every 10 years on a 50 year rotation period. This strategy leads to an increase in stand C stock compared to the current Aspen management strategy where there is no regard to temporal heterogeneity of harvests (Figure 22). The landscape successional mosaic strategy and the altered rotation periods are not necessarily mutually exclusive management scenarios. While not considered explicitly in the present

analysis, altered rotation periods could be combined with a landscape level strategy resulting in an altered Aspen maintenance strategy at a landscape level. Regardless of rotation length chosen, one of the major benefits to this strategy is a stabilization of income flow resulting from a more constant timber flow, in sharp contrast to the “boom and bust” strategy currently employed. This stabilization in timber flow level is accompanied by stabilization of C stock and diversity as well.

The stand present value is lower with the landscape successional mosaic strategy than with the other Aspen maintenance strategies because the sales occur further into the future and are, thus, impacted by discounting. However, this is a product of the assumption made that all harvests occurred in year 1. This assumption is based on a starting point of a set of similarly aged Aspen stands, representative of actual conditions in Michigan forests. Were the Aspen stands across the landscape initially of mixed age, the results could be affected. This assumption also impacts the total harvest volume. While theoretically, the total harvest volume with the landscape mosaic strategy should be the same as the current Aspen management strategy, 80% of stands in the simulation benefited from additional growth prior to their initial harvest resulting in a higher timber volume in addition to a higher level of diversity and C stored in the first 50 years of the simulation.

As the majority of maturing Aspen stands in northern lower MI have a Northern Hardwood dominated understory, if this strategy was applied across the landscape, many Aspen stands would convert to the Northern Hardwood cover type. Considering the diverse objectives that must be met, it is unlikely that the optimal strategy for FMU managers in MI would be to convert all Aspen stands to late successional species covers. Optimal management at the landscape level would likely include a combination of different management strategies. If this landscape successional mosaic strategy were employed on a certain percentage of current Aspen stands in an FMU, the rotation period of these stands was increased to 60 or 90 years and the remainder of the stands were allowed to convert to later successional cover types, a constant supply of timber profits from Aspen harvests could be combined with an increase in C stock across the landscape. In a study in the Great Lakes, Gustafson *et al.*(2003) suggested a strategy of growing Aspen only on the most productive sites and allowing less productive sites to be converted to other species cover. Because MITRIX does not designate a site index, exploring this scenario was not an

option. However, it does illustrate the importance of site specific landscape knowledge in casting management prescriptions. Using the scenarios analyzed here and scaling up to the landscape level is one step in aiding landscape level decisions. However, knowledge of individual sites is necessary for the best site management.

Economic Analysis

The Aspen management scenarios result in a much higher stand PV compared to the scenarios that maximized C storage. In all Aspen maintenance strategies, a significant harvest occurs early in the simulation, resulting in timber profits being minimally affected by discount rates. These strategies also result in a greater timber volume over time, as Aspen are faster growing trees than the later successional Hardwoods. As calculated, stand PV for all sub-strategies within the allow succession scenario is markedly lower than that for maintaining Aspen dominated stands (Table 8). Of the sub-strategies, selective cutting of Hardwoods resulted in the highest PV followed by a delayed Hardwood harvest results. The increase in stand PV from the late Hardwood harvest was small as the harvest occurs far into the future.

Valuing C

Many studies have considered the price of C needed to balance decreases in timber profits, with the conclusions about the cost of C sequestration highly site dependent and variable depending on assumptions made about the definition of a ton of C, the ecosystem components included in the analysis, rates of C uptake, and opportunity costs (see Richards and Stokes, 2004 for a review). Assuming that only on site C and timber profits are considered, the value of a metric ton of C (equal to one Mg of C and hereby referred to as a ton of C) was calculated in this analysis by dividing the net loss in timber profits by the net gain in C. The analysis here suggests that with a 200 year time frame of analysis and assuming a discount rate of 0.04 for timber profits and 0.02 for C, a ton of C would need to be worth \$22-26 in order for the conversion management strategy to be economically equal to the current Aspen strategy. This is less than the current value of a ton of C on the European carbon market (European Climate Exchange, 2008), but substantially higher than the value of a ton of C on the voluntary carbon market in the US (Chicago Climate Exchange, 2008). Currently the C market in the US is a strictly voluntary market run by the Chicago Climate Exchange. As of July 2008, a ton of C was

trading for approximately \$5 (Chicago Climate Exchange, 2008). This is substantially lower than the calculated price needed. On the non-voluntary European carbon market, however, the price of a ton of C on was approximately €27, or \$42 as of July 2008 (European Climate Exchange, 2008). Were the US to adopt a mandatory C trading scheme that was comparable to that of the EU, the economic gain from increased C compared to the current management strategy would more than balance the lower profits from timber sales.

In considering the impacts of C revenues on pine plantation forestry in the south central United States, Sohngen and Brown (2006) suggest that maintaining Hardwood forests rather than converting them to pine plantations would be an economically beneficial strategy if C offsets were given an economic value. In this study, the break-even price supporting this result depends on the time frame of the analysis. For a 100 or 200 year time frame, a reasonable time frame for climate change related issues, the price of carbon that would support Hardwood forest succession is \$20-30 per ton of C. The prices estimated in this analysis falls within the range of values of other analyses (see Richards and Stokes, 2004).

Carbon storage in wood products is not considered in this analysis. Including this stock could have important implications on the estimated necessary C value as including this pool would increase the C value associated with harvest, thereby decreasing the net C gain from allowing succession. Many C accounting models with forest applications include the forest product pool (e.g. Masera *et al.*, 2003). Incorporating the forest product C pool buffers the impact of harvesting on C stocks as some C remains in the product pool. This would have important implications for quantifying C offsets from management activities. While excluding this pool does not affect the ability to address impacts and tradeoffs associated with C storage goals, if the state could get credit for C sequestered in paper and wood products, it could make the Aspen maintenance scenarios more desirable.

Discount Rates

The choice of discount rate can have important implications on the outcome of an analysis. A discount rate of 0.04 for timber profits has been used in several similar applications (e.g. Spring *et al.*, 2005; Neilson *et al.*, 2006). Altering the discount rate of timber profits affects the management strategy that has the greatest stand PV. In this analysis, when a discount rate of

0.04 was used for timber profits, a 60 year rotation period resulted in the greatest stand PV, though the values for the four different rotation lengths were very similar. When the discount rate was lowered, a longer rotation period was favored. Lowering the discount rate to zero highlights the impacts on assumptions of the time that a harvest takes place. Scenarios that assume harvests longer into the future have high undiscounted stand PV, but low discounted stand PV. Using a zero discount rate is not a practical scenario as future economic profits are rarely, if ever, considered equivalent to present economic profits. That said, it has been argued that discounting renewable resources such as forests is problematic as it will usually favor early harvests. Finding ways to value non-timber services is one potential way to deal with this problem.

Selecting a discount rate for C is challenging. If discounting is not used for C, it has been argued that there will be a bias towards C sequestration far into the future (Krcmar *et al.*, 2005). Other studies have also included a discount rate for C (e.g. Neilson *et al.*, 2006). In this analysis, altering the amount that future C storage is discounted does not change the relative impact for the different scenarios. However, it does change the perceived amount of net C stock change for each individual scenario and, as a result, the calculated C value necessary to offset differences in timber revenue between scenarios. A low discount rate for C favors scenarios that push C sequestration off into the future while maximizing timber profits in the short run, as future C gain is valued almost as much as current C gains. At the same time, if a high discount rate is used, the value given to C to offset lost timber revenue would need to be very high, as the net gains from altered C management scenarios would be tempered. Others have argued that discount rates should be lower for environmental services like C storage because people tend to maintain a sense of value for them into the future compared to financial profits (Krcmar *et al.*, 2005). Given this, a discount rate of 0.02 for C in combination with a discount rate of 0.04 for timber revenue was chosen for this study.

Shifting the Time Frame

Stand level management decisions in Michigan are prescribed on a 10 year time interval. Assuming that this is the time frame of analysis for considering future profits and C storage, this has important implications for the optimal strategy. A shorter time frame favors short term

profits and does not account for long term C storage or timber profits in the distant future. This affects the optimal strategy when just timber profits are considered as well as when C storage is considered. This is especially important when considering the price of C necessary to offset the displaced timber profits for the succession management scenario. The results here indicate that, for a short time frame of analysis (10 years) the price of a ton of C would need to exceed \$200 for the profits to be offset. Increasing the timeframe of analysis may be necessary for management strategies targeting C storage to be profitable.

In addition to having an impact on the results of this analysis, the time frame of analysis is important when considering sustainable forest management (SFM). SFM has been defined as “managing forest resources to meet society’s varied needs, today and tomorrow, without compromising the ecological capacity and the renewal potential of the forest resource base” (Wang, 2004). The key in this definition and what is at the heart of SFM is attention to the future, presumably both the near and distant future. For SFM to be achieved, a shift to a long time frame of analysis is essential.

Diversity

Stand diversity was affected by the various management scenarios. Maintaining diversity is another potential management objective and the results show that it is increased with increasing the rotation period and with the C-maximizing strategy of allowing succession to a new cover type. Higher average diversity in this analysis correlated with greater net C impact. Other studies have also found links between diversity and C storage (e.g. Eriksson and Hammer, 2006). Changing the management strategy to a landscape level perspective and allowing succession both result in slightly higher diversity indices as well as increased stability in the stand diversity when compared to the reference case. Diversity was not included in the economic analysis here, but it is important to consider when selecting a management strategy, as increased diversity increases the resilience of a forest stand, which improves the ability of a stand to withstand a disturbance (Naeem and Li, 1997; Elmqvist *et al.*, 2003). This has an impact on the sustainability of a management strategy as forest stands that can recover from disturbance events are more likely to be more sustainable. Mixed species forests are more stable and have lower rates of soil organic matter decomposition (Madritch and Cardinale, 2007). When considering C storage in

combination with diversity, Noss (2001) warns of the dangers of managing forests for C alone because of the key link between diversity and the long term sustainability and resilience of forest ecosystems (Noss, 2001).

The Future of C and Michigan Forest Management

MITRIX provides a way to consider how varying forest management prescriptions affects the amount of C stored in a forest stand, the diversity of the stand, and the stand PV resulting from timber sales. Overall, the model application suggests that maximal C storage is achieved through allowing the stand to succeed to a later successional species cover. While there is likely a limit to the extent to which management of Michigan forests will contribute to an overall reduction in atmospheric CO₂, different management prescriptions do result in different amounts of C stored. The new state forest management plan sets the stage for incorporating C storage in to forest management decisions in Michigan and the rising societal focus on climate change and atmospheric CO₂ levels suggests that the issue of reducing atmospheric C will continue in coming years. The role of Michigan forest management in mitigating CO₂ emissions will depend on the relative balance of other objectives. MITRIX represents a way for forest managers to look at how incorporating C storage may affect other management priorities. It also provides a way to consider long term implications of various decisions, which is important for successful sustainable forest management.

Wolfslehner *et al.* (2005) proposed that the practice of forestry worldwide is in the midst of a paradigm shift from sustained yield to sustainable forestry. The increased emphasis on forest certification, at least in the developed world, is evidence of this shift. The state managed forests of Michigan are following the course of many forests across the developed world. Wolfslehner *et al.* (2005) suggest that there are six major components of sustainable forestry. These include protecting diverse resources and C cycles, maintaining forest health and vitality, maintaining production, preserving biodiversity, ensuring protection to water and soil, and maintaining other socioeconomic functions. While C storage is certainly an important function of forest ecosystems, ultimately, sound forest management will need to consider balance of competing objectives. Future modeling will provide the tools necessary in this endeavor as well as identify gaps in scientific and policy implementation.

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APPENDIX I – UMBS Stem Map Methods and Results

Methods

In order to generate baseline data of a typical stand composition of an 80-90 year old unmanaged forest, detailed inventory data were created from four unmanaged forests stands at the University of Michigan Biological Station (UMBS) in northern lower Michigan. The UMBS property is located south of Douglas Lake and east of Pellston, MI (approximately 45.6°N 84.7°W). Two stem maps were generated within each of two sites at the UMBS: The Detritus Input and Removal Treatment (DIRT) site and the Forest Accelerated Succession Experiment (FASET). The DIRT maps are of quarters 1 and 3. The FASET maps contain intensive centers D2 (FASET A) and B1 (FASET B).

For each map, a 100m x 100m grid was set using an engineer's level and measuring tape. Eighteen inch long sections of ½ inch PVC pipe were labeled with corresponding vertex numbers and hammered into the ground 10m apart to form the grid. The grid markers at the DIRT location were labeled according to a numbering system proposed by James LeMoine, while those at the FASET site were labeled according to a system devised in the present study. After the grid was set, 20m x 20m sections were roped off for surveying.

All stems with a diameter at breast height (approximately 1.37m from the ground) of 1.0 cm or greater were tagged and identified. Stems were considered unique if branching occurred anywhere below breast height. Species, status, canopy position, and exact spatial location were recorded (Table 12-14). Tree location was determined by placing an engineer's level at the center of each 20m x 20m section and recording the angle and distance of the center base of each stem from the center point. A coordinate system transformation was then performed to give each stem a location in a Cartesian coordinate system. The (0,0) location corresponded to the southwest corner of each hectare.

Following field data collection, all data were compiled into a geodatabase. A GIS was then created for each database. Summary statistics for each location were generated. These data were

then aggregated to generate information about unmanaged forest stands. Size distributions and species composition were analyzed. Biomass was then estimated through allometric equations.

Table 12. List of species found and recorded in the four stem map sites at the University of Michigan Biological Station (UMBS) in 2006 and 2007.

Species Code	Scientific Name	Common Name
abba	<i>Abies balsamea</i>	Balsam Fir
acpe	<i>Acer pensylvanicum</i>	Striped Maple
acru	<i>Acer rubrum</i>	Red Maple
acsa	<i>Acer saccharum</i>	Sugar Maple
amar	<i>Amelanchier arborea</i>	Downy Serviceberry
amla	<i>Amelanchier laevis</i>	Smooth Serviceberry
bepa	<i>Betula papyrifera</i>	Paper or White Birch
fagr	<i>Fagus grandifolia</i>	American Birch
osvi	<i>Ostrya virginiana</i>	Ironwood
pire	<i>Pinus resinosa</i>	Red Pine
pist	<i>Pinus strobus</i>	White Pine
pogr	<i>Populus grandidentata</i>	Bigtooth Aspen
potr	<i>Populus tremuloides</i>	Trembling Aspen
prse	<i>Prunus serotina</i>	Black Cherry
quru	<i>Quercus rubra</i>	Red Oak

Table 13. List of stem status codes and description. Every stem recorded was designated a status. A stem was designated L if it was alive, D if the stem was dead, and M if the stem was alive, but very nearly dead (i.e. if leaves were present on only one branch, if the majority of branches were dead, or if the stem appeared unhealthy).

Status Code	Description
L	Live
M	Moribund (nearly dead)
D	Dead

Table 14. Description of canopy positions recorded. Every stem was designated a canopy position based on observation of relative position in the canopy or sub-canopy.

Canopy Position	Description
OD	Overstory Dominant
OS	Overstory Subdominant
U	Understory
S	Sapling

Results

All four stands were dominated by mature *Populus grandidentata* (Figure 25). Other common species included *Acer rubrum*, *Betula papyrifera*, *Pinus strobus*, and *Quercus rubra*. Other species present included *Acer pensylvanicum*, *Acer saccharum*, *Amelanchier spp.*, *Fagus grandifolia*, *Ostrya virginiana*, *Pinus resinosa*, *Populus tremuloides*, and *Prunus serotina*. The total number of stems per ha followed a J-shaped distribution typical of unmanaged forests (Figure 26). Stem counts by canopy position for the four stands are shown in Tables 15-18. Live basal area by species for the four sites is shown in Tables 19-22. Total aboveground biomass is shown in Tables 23-26. The creation of GIS data layers yielded spatial maps of all stems in the four stands (Figures 27-30).

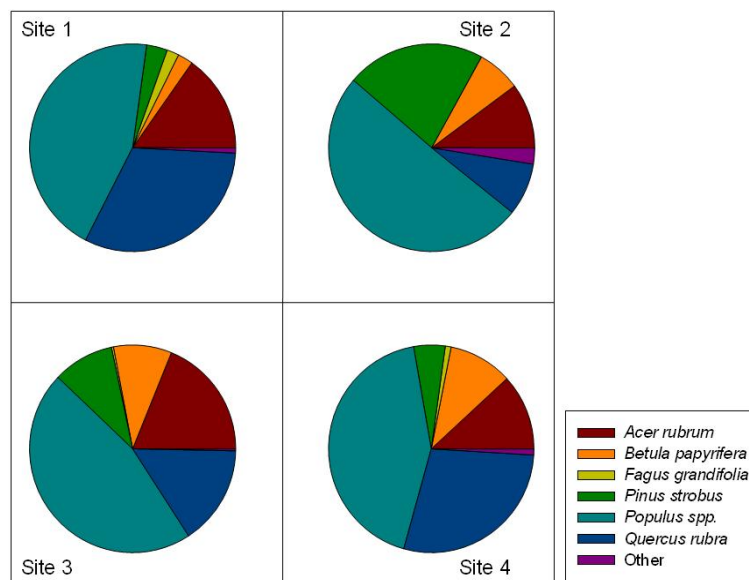


Figure 25. Percent of total basal area by species for each of the four 1 ha sites at the UMBS. Sites 1 and 2 are within the FASET study area, FASET A and FASET B respectively. Sites 3 and 4 are within the DIRT study site, Q1 and Q3 respectively.

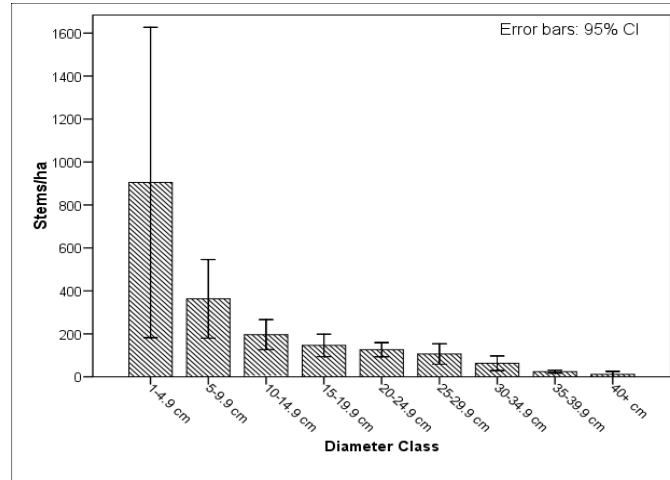


Figure 26. Mean stems ha⁻¹ for all species in four 1 ha stem maps at the UMBS.

Table 15. Stem count by canopy position for the Quarter 1 stem map in the DIRT study site at the UMBS.

Species	S	U	OS	OD	Dead	Total
<i>Abies balsamea</i>	1					1
<i>Acer rubrum</i>	136	302	113	17	20	588
<i>Amelanchier arborea</i>	2					2
<i>Amelanchier laevis</i>	14	4			1	19
<i>Betula papyrifera</i>	7	19	26	43	27	122
<i>Fagus grandifolia</i>	7	33				40
<i>Pinus resinosa</i>	2	1	3	1		7
<i>Pinus strobus</i>	32	106	21	2	1	162
<i>Populus grandidentata</i>	2	9	9	178	40	238
<i>Populus tremuloides</i>		1				1
<i>Quercus rubra</i>	95	73	8	75	5	256
Total	298	548	180	316	94	1436

Table 16. Stem count by canopy position for the Q3 stem map in the DIRT study site at the UMBS.

Species	S	U	OS	OD	Dead	Total
<i>Acer rubrum</i>	98	134	147	39	27	445
<i>Amelanchier arborea</i>	7					7
<i>Betula papyrifera</i>	1	19	34	30	44	128
<i>Fagus grandifolia</i>	6	15				21
<i>Pinus resinosa</i>	2		3			5
<i>Pinus strobus</i>	265	119	48	5	1	438
<i>Populus grandidentata</i>	3	1	24	200	35	263
<i>Populus tremuloides</i>			1			1
<i>Quercus rubra</i>	128	43	6	40	1	218
Total	510	331	263	314	108	1526

Table 17. Stem count by canopy position for the FASET A stem map at the UMBS.

Species	S	U	OS	OD	Dead	Total
<i>Acer pensylvanicum</i>	62	109			1	172
<i>Acer rubrum</i>	153	499	158	15	29	854
<i>Acer saccharum</i>		5	2			7
<i>Amelanchier arborea</i>	10	3				13
<i>Amelanchier laevis</i>	53	47				100
<i>Betula papyrifera</i>		10	6	10	19	45
<i>Fagus grandifolia</i>	12	89	6		3	110
<i>Ostrya virginiana</i>		1				1
<i>Pinus strobus</i>	118	180	8	1	2	309
<i>Populus grandidentata</i>			7	225	36	268
<i>Prunus serotina</i>	1					1
<i>Quercus rubra</i>	14	67	83	114	41	319
						0
Total	423	1010	270	365	131	2199

Table 18. Stem count by canopy position for the FASET B stem map at the UMBS.

Species	S	U	OS	OD	Dead	Total
<i>Acer pensylvanicum</i>	8	7				15
<i>Acer rubrum</i>	166	396	81	17	2	662
<i>Acer saccharum</i>		1	2			3
<i>Amelanchier arborea</i>	31	22				53
<i>Amelanchier laevis</i>	177	381	9		1	568
<i>Betula papyrifera</i>	1	4	11	38	5	59
<i>Fagus grandifolia</i>	4	2				6
<i>Ostrya virginiana</i>		1				1
<i>Pinus resinosa</i>	1	4		1		6
<i>Pinus strobus</i>	88	254	97	23	4	466
<i>Populus grandidentata</i>	2	10	37	211	40	300
<i>Populus tremuloides</i>		7	5	15	11	38
<i>Prunus serotina</i>		4				4
<i>Quercus rubra</i>	76	306	39	19		440
						0
Total	554	1399	281	324	63	2621

Table 19. Live basal area by species for the Q1 stem map in the DIRT study site at the UMBS.

Species	Live Basal Area (m²)
<i>Abies balsamea</i>	0.00
<i>Acer rubrum</i>	2.60
<i>Amelanchier arborea</i>	0.00
<i>Amelanchier laevis</i>	0.00
<i>Betula papyrifera</i>	2.20
<i>Fagus grandifolia</i>	0.20
<i>Pinus resinosa</i>	0.20
<i>Pinus strobus</i>	1.08
<i>Populus grandidentata</i>	9.36
<i>Populus tremuloides</i>	0.00
<i>Quercus rubra</i>	6.21
Total	21.85

Table 20. Live basal area by species for the Q3 stem map in the DIRT study site at the UMBS.

Species	Live Basal Area (m²)
<i>Acer rubrum</i>	4.64
<i>Amelanchier arborea</i>	0.00
<i>Betula papyrifera</i>	2.23
<i>Fagus grandifolia</i>	0.08
<i>Pinus resinosa</i>	0.06
<i>Pinus strobus</i>	2.35
<i>Populus grandidentata</i>	11.30
<i>Populus tremuloides</i>	0.04
<i>Quercus rubra</i>	3.83
Total	24.53

Table 21. Live basal area by species for the FASET A stem map at the UMBS.

Species	Live Basal Area (m ²)
<i>Acer pensylvanicum</i>	0.13
<i>Acer rubrum</i>	4.76
<i>Acer saccharum</i>	0.08
<i>Amelanchier arborea</i>	0.00
<i>Amelanchier laevis</i>	0.03
<i>Betula papyrifera</i>	0.74
<i>Fagus grandifolia</i>	0.59
<i>Ostrya virginiana</i>	0.00
<i>Pinus strobus</i>	1.01
<i>Populus grandidentata</i>	13.84
<i>Prunus serotina</i>	0.00
<i>Quercus rubra</i>	9.88
Total	31.08

Table 22. Live basal area by species for the FASET B stem map at the UMBS.

Species	Live Basal Area (m ²)
<i>Acer pensylvanicum</i>	0.01
<i>Acer rubrum</i>	2.75
<i>Acer saccharum</i>	0.01
<i>Amelanchier arborea</i>	0.02
<i>Amelanchier laevis</i>	0.47
<i>Betula papyrifera</i>	1.83
<i>Fagus grandifolia</i>	0.01
<i>Ostrya virginiana</i>	0.00
<i>Pinus resinosa</i>	0.15
<i>Pinus strobus</i>	5.83
<i>Populus grandidentata</i>	13.01
<i>Populus tremuloides</i>	0.60
<i>Prunus serotina</i>	0.00
<i>Quercus rubra</i>	2.21
Total	26.92

Table 23. Total aboveground biomass for the Q1 stem map in the DIRT study site at the UMBS.

Species	Total Above-Ground Biomass (kg)
<i>Abies balsamea</i>	1
<i>Acer rubrum</i>	11,848
<i>Amelanchier arborea</i>	1
<i>Amelanchier laevis</i>	21
<i>Betula papyrifera</i>	12,405
<i>Fagus grandifolia</i>	1,302
<i>Pinus resinosa</i>	759
<i>Pinus strobus</i>	2,977
<i>Populus grandidentata</i>	48,044
<i>Populus tremuloides</i>	1
<i>Quercus rubra</i>	45,775
Total	123,134

Table 24. Total aboveground biomass for the Q3 stem map in the DIRT study site at the UMBS.

Species	Total Above-Ground Biomass (kg)
<i>Acer rubrum</i>	22,483
<i>Amelanchier arborea</i>	4
<i>Betula papyrifera</i>	12,482
<i>Fagus grandifolia</i>	452
<i>Pinus resinosa</i>	209
<i>Pinus strobus</i>	6,048
<i>Populus grandidentata</i>	58,534
<i>Populus tremuloides</i>	120
<i>Quercus rubra</i>	27,928
Total	140,990

Table 25. Total aboveground biomass by species for the FASET A stem map at the UMBS.

Species	Total Above-Ground Biomass (kg)
<i>Acer pensylvanicum</i>	426
<i>Acer rubrum</i>	21,979
<i>Acer saccharum</i>	499
<i>Amelanchier arborea</i>	8
<i>Amelanchier laevis</i>	156
<i>Betula papyrifera</i>	4,377
<i>Fagus grandifolia</i>	4,084
<i>Ostrya virginiana</i>	1
<i>Pinus strobus</i>	2,668
<i>Populus grandidentata</i>	73,725
<i>Prunus serotina</i>	0
<i>Quercus rubra</i>	66,747
Total	174,670

Table 26. Total aboveground biomass by species for the FASET B stem map at the UMBS.

Species	Total Above-Ground Biomass (kg)
<i>Acer pensylvanicum</i>	22
<i>Acer rubrum</i>	13,625
<i>Acer saccharum</i>	68
<i>Amelanchier arborea</i>	105
<i>Amelanchier laevis</i>	2,891
<i>Betula papyrifera</i>	11,560
<i>Fagus grandifolia</i>	83
<i>Ostrya virginiana</i>	1
<i>Pinus resinosa</i>	672
<i>Pinus strobus</i>	18,805
<i>Populus grandidentata</i>	78,948
<i>Populus tremuloides</i>	2,321
<i>Prunus serotina</i>	7
<i>Quercus rubra</i>	13,877
Total	142,985

Stem Map of Quarter 1 in the DIRT Study Site University of Michigan Biological Station Pellston, MI June 2007

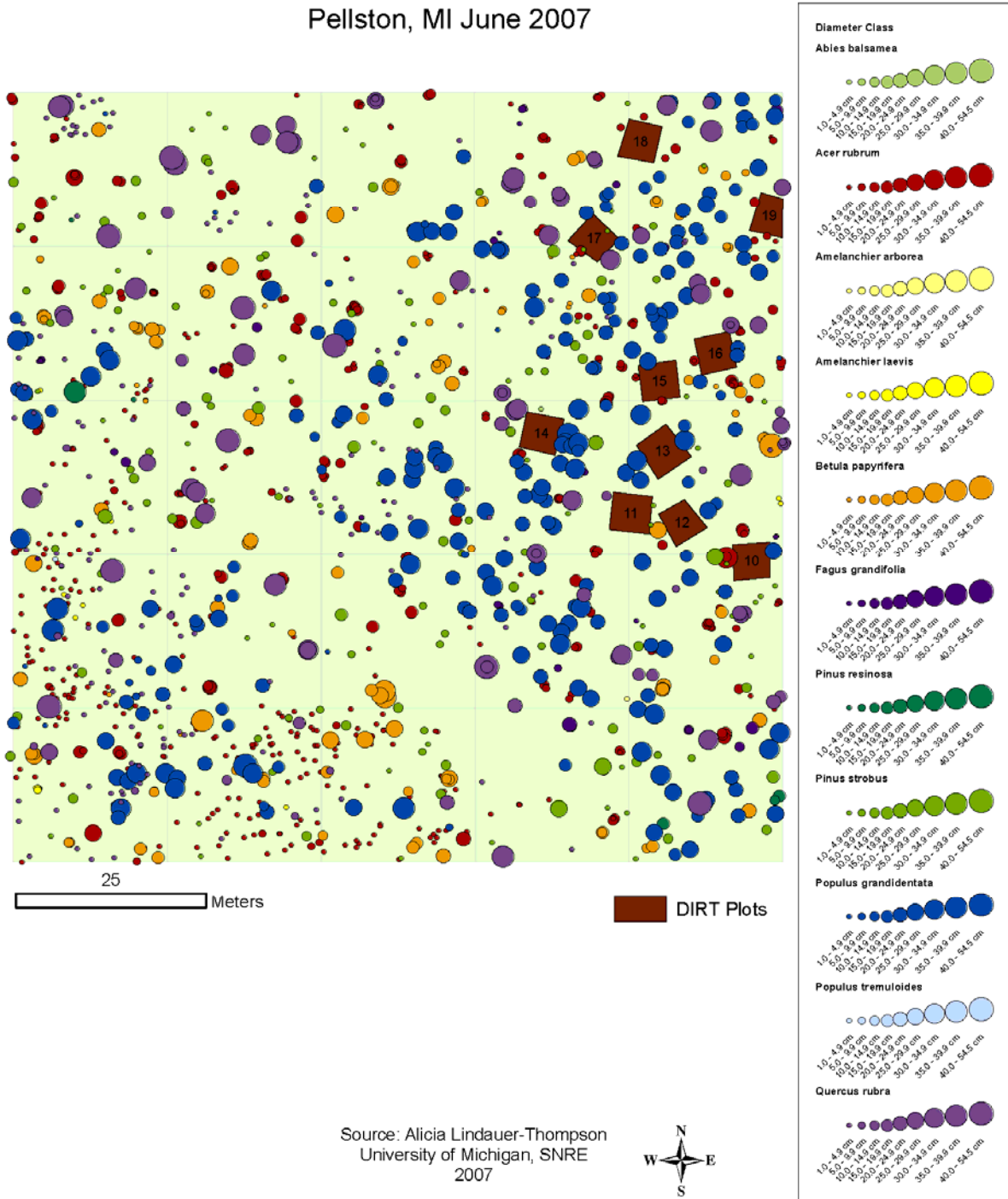


Figure 27. Spatial location of all trees and study plots in Quarter 1 of the DIRT study site at the UMBS.

Stem Map of Quarter 3 in the DIRT Study Site University of Michigan Biological Station Pellston, MI June 2006

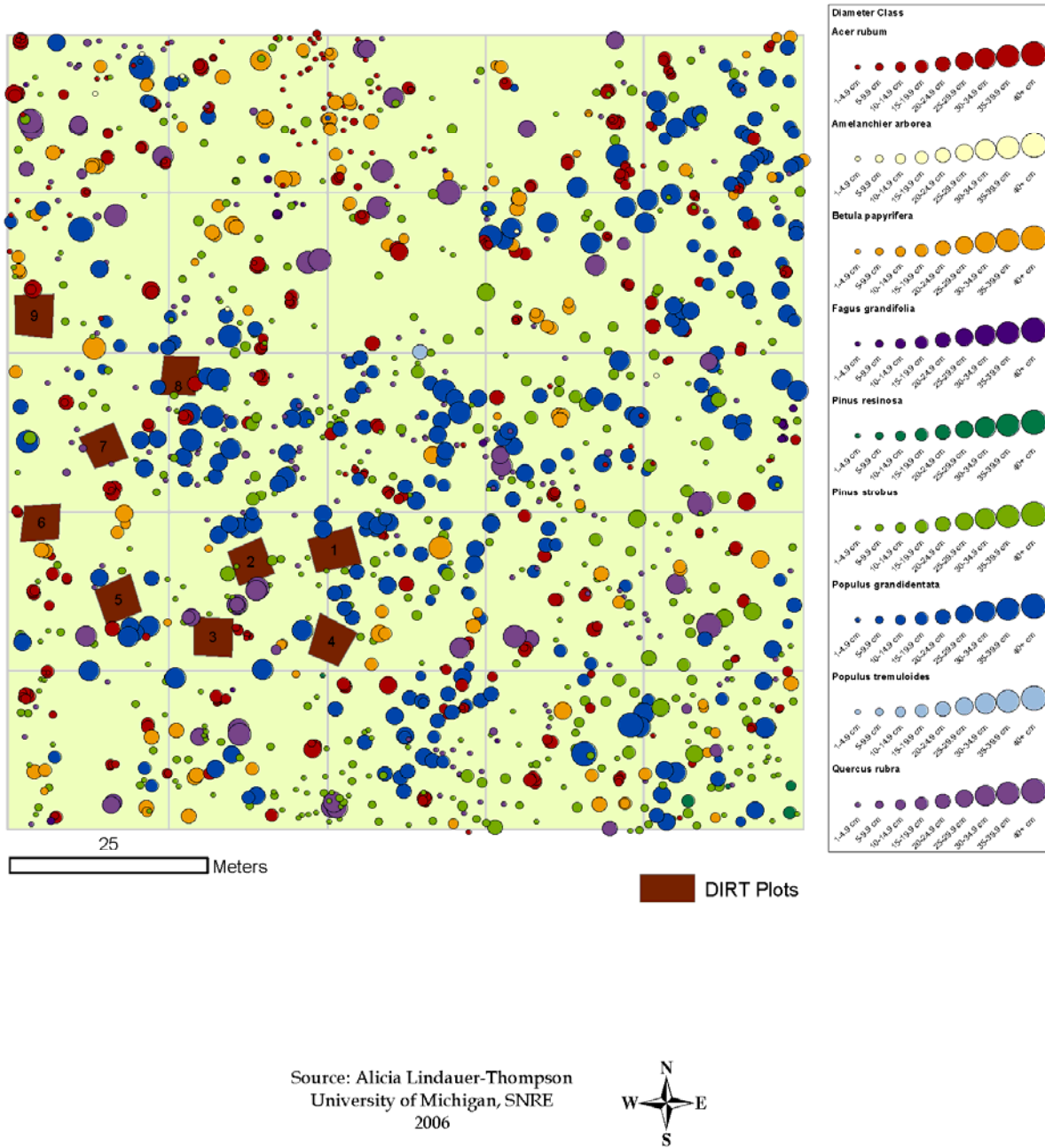


Figure 28. Spatial location of all trees and study plots in Quarter 3 of the DIRT study site at the UMBS.

Stem Map within the FASET Study Site University of Michigan Biological Station Pellston, MI July-August 2007

FASET A - Near Intensive Site D2

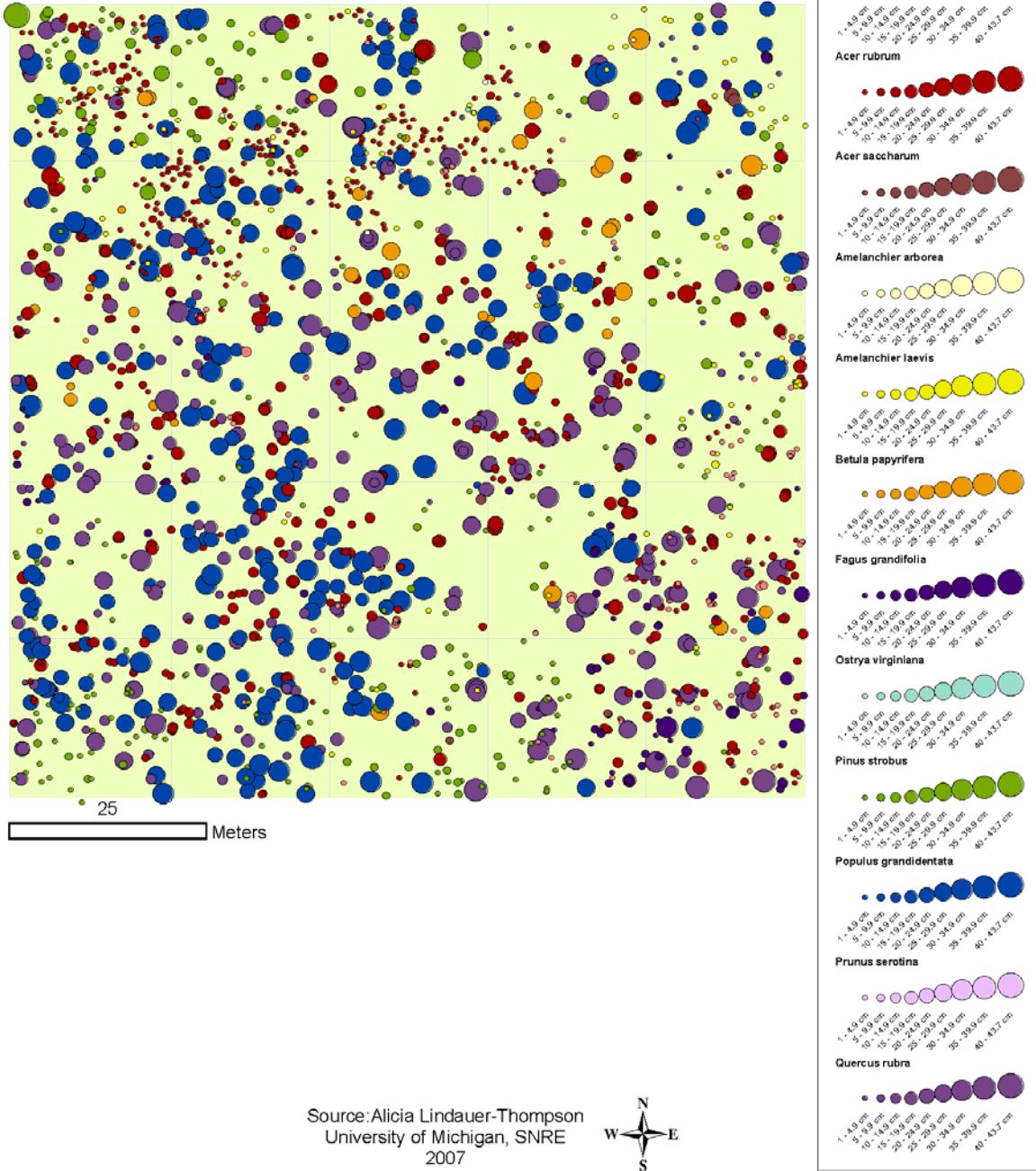


Figure 29. Spatial location of all trees in one ha of the FASET study site at the UMBS (FASET A).

Stem Map within the FASET Study Site

University of Michigan Biological Station

Pellston, MI July-August 2007

FASET B - Near Intensive Site B1

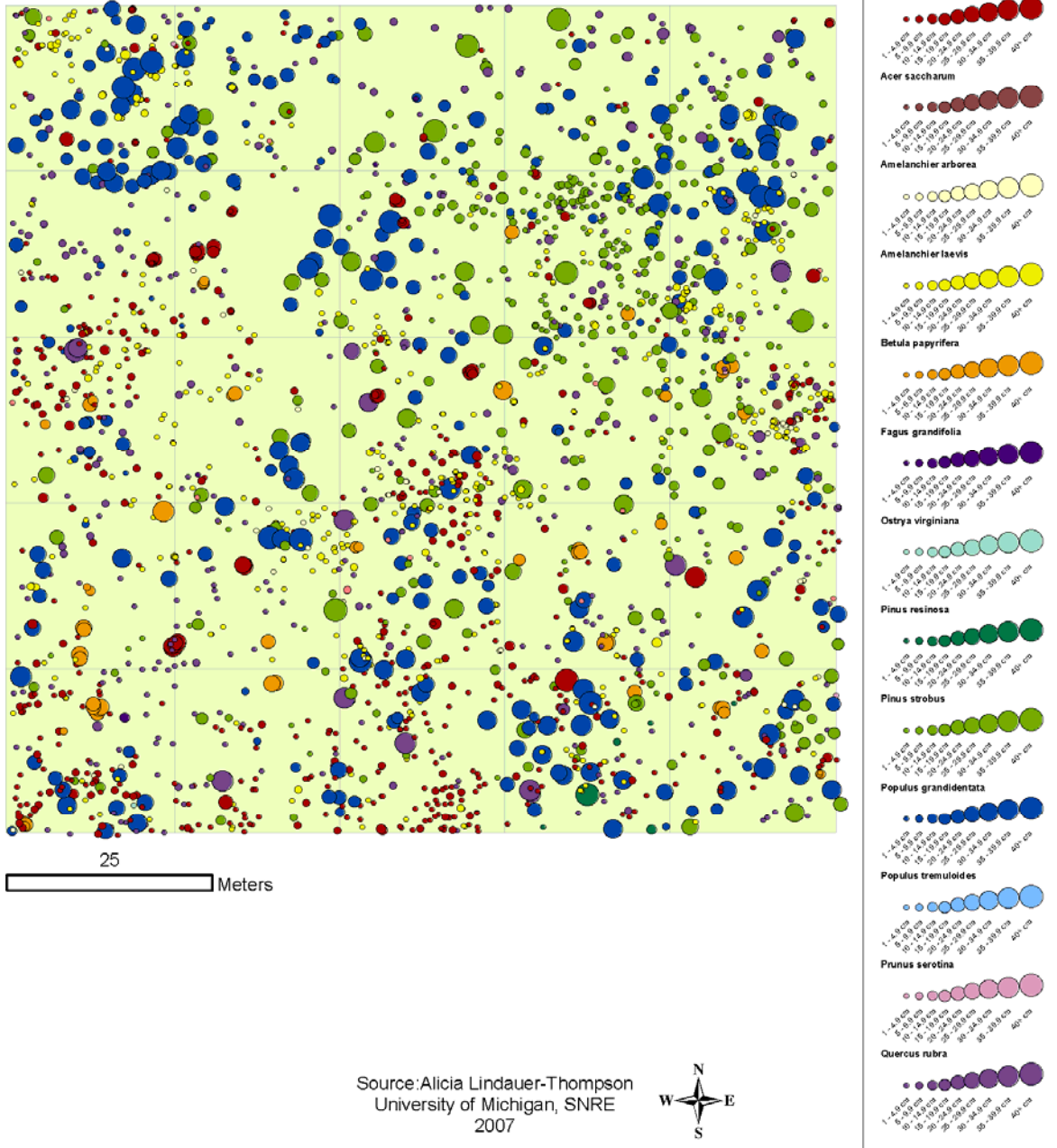


Figure 30. Spatial location of all trees in one ha of the FASET study site at the UMBS (FASET B).

APPENDIX II – MITRIX Code

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MITRIX (MICHigan maTRIX:
%           a model for decision support in state-owned
%           forest management in Michigan)
% Created by: Alicia Lindauer-Thompson, University of Michigan

% The following model was coded in MATLAB as a major component of the
Master's thesis work of Alicia Lindauer-Thompson at the University of
Michigan, School of Natural Resources and Environment

% All rights reserved 2007-2008

% % Species abbreviations:
% acru = Acer rubrum
% acaa = Acer saccharum
% bepa = Betula papyrifera
% fagr = Fagus grandifolia
% pist = Pinus strobus
% pogr = Populus grandidentata
% potr = Populus tremuloides
% quru = Quercus rubra
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Define Initial Stand State
% Define vector of size distribution at time 0 for each species

S=load('Initial_State_Model.txt'); %text file from Excel sheet
s_acru=S(:,2);
s_bepa=S(:,3);
s_acsa=S(:,4);
s_fagr=S(:,5);
s_pist=S(:,6);
s_pogr=S(:,7);
s_quru=S(:,8);
s_st=S(:,9);
s_mt=S(:,10);
s_it=S(:,11);

% Put species vectors into a single vector
s_t=[s_acru;s_bepa;s_acsa;s_fagr;s_pist;s_pogr;s_quru;s_st;s_mt;s_it];

%% Equations for growth model parameters

% MORTALITY
% Coefficients from Kolbe et al 1999 for Michigan forests
% Shade tolerant species
delta_0_st=.034;
delta_1_st=.00019;
delta_2_st=-0.14;
delta_3_st=0.22;

```

```

% Midtolerant species
delta_0_mt=0.036;
delta_1_mt=0.00052;
delta_2_mt=-0.20;
delta_3_mt=0.27;

% Shade intolerant species
delta_0_it=0.05;%changed from 0.052
delta_1_it=0;
delta_2_it=-0.19;
delta_3_it=0.22;

    dbh=[2.5,7.5,12.5,17.5,22.5,27.5,32.5,37.5,45]; % dbh of average tree in
each size class (cm)
dbh=dbh/100; % Convert cm to m
B=pi()*(dbh/2).^2; % Basal area of average tree in each size class (m^2)

stand_BA=5; % Assume a stand basal area for parameter calculations

% Equations to generate probability of mortality for each size class (varies
% by shade tolerance, modified from Lin and Buongiorno 1996 and Kolbe et
% al 1999.

% d is the probability of a tree dying in each time step, calibrated to one
% year
for j=1:9    %j is size class

d_st(j)=delta_0_st+(delta_1_st*stand_BA)+(delta_2_st*(dbh(j)))+(delta_3_st*(db
h(j)).^2));

d_mt(j)=delta_0_mt+(delta_1_mt*stand_BA)+(delta_2_mt*(dbh(j)))+(delta_3_mt*(db
h(j)).^2));

d_it(j)=delta_0_it+(delta_1_it*stand_BA)+(delta_2_it*(dbh(j)))+(delta_3_it*(db
h(j)).^2));
end

% UPGROWTH
% Coefficients from Kolbe et al 1999 for Michigan forests
% Shade tolerant species
beta_0_st=0.013;
beta_1_st=-0.00085;
beta_2_st=0.23;
beta_3_st=-0.40;

% Midtolerant species
beta_0_mt=0.016;
beta_1_mt=-0.0011;
beta_2_mt=0.25;
beta_3_mt=-0.43;

% Shade intolerant species
beta_0_it=0.009;
beta_1_it=-0.0004;

```

```

beta_2_it=0.21;
beta_3_it=-0.40;

% b is the probability of a tree in size class j of moving into the next
% size class in the next time step, calibrated to one year

for j=1:9 % j is size class

b_st(j)=beta_0_st+(beta_1_st*stand_BA)+(beta_2_st*dbh(j))+(beta_3_st*dbh(j).^
2);

b_mt(j)=beta_0_mt+(beta_1_mt*stand_BA)+(beta_2_mt*dbh(j))+(beta_3_mt*dbh(j).^
2);

b_it(j)=beta_0_it+(beta_1_it*stand_BA)+(beta_2_it*dbh(j))+(beta_3_it*dbh(j).^
2);
end

% a is the probability of a tree in size class j remaining in that size
% class in the next time step a=1-b-d

for j=1:8
    a_st(j)=1-b_st(j)-d_st(j);
    a_mt(j)=1-b_mt(j)-d_mt(j);
    a_it(j)=1-b_it(j)-d_it(j);
end
for j=9
    a_st(j)=1-d_st(j);
    a_mt(j)=1-d_mt(j);
    a_it(j)=1-d_it(j);
end

for i=1:9
    for j=1:9
        if i==j
            A_st(i,j)=a_st(j);
            A_mt(i,j)=a_mt(j);
            A_it(i,j)=a_it(j);

        else if i==j+1
            A_st(i,j)=b_st(j);
            A_mt(i,j)=b_mt(j);
            A_it(i,j)=b_it(j);

        else
            A_st(i,j)=0;
            A_mt(i,j)=0;
            A_it(i,j)=0;
        end
    end
end
end
end

```

```

% INGROWTH
% Coefficients from Kolbe et al 1999 for Michigan forests

% Shade tolerant
alpha_0_st=34;
alpha_1_st=-0.5;
alpha_2_st=0;

% Midtolerant
alpha_0_mt=12;
alpha_1_mt=-0.5;
alpha_2_mt=0.004;

% Intolerant
alpha_0_it=22;
alpha_1_it=-0.9;
alpha_2_it=0.006; % changed 3-9-08 to match Lin et al 1996

% build matrices for each species type
for j=1:9 % j is size class
    for k=1:9
        if k==1
            R_st_st(k,j)=alpha_1_st*B(j)+alpha_2_st; % effect of shade tolerant
own species
            R_st(k,j)=alpha_1_st*B(j); % effect other species on shade tolerant

            R_mt_mt(k,j)=alpha_1_mt*B(j)+alpha_2_mt; % effect of midtolerant on
own species
            R_mt(k,j)=alpha_1_mt*B(j); % effect other species on midtolerant

            R_it_it(k,j)=alpha_1_it*B(j)+alpha_2_it; % effect intolerant on own
species
            R_it(k,j)=alpha_1_it*B(j); % effect of other species on intolerant

        else
            R_st_st(k,j)=0;
            R_st(k,j)=0;

            R_mt_mt(k,j)=0;
            R_mt(k,j)=0;

            R_it_it(k,j)=0;
            R_it(k,j)=0;
        end
    end
end

% stand independent recruitment
c_st=[alpha_0_st;zeros(8,1)];
c_mt=[alpha_0_mt;zeros(8,1)];
c_it=[alpha_0_it;zeros(8,1)];

```

```

%% Transition Probability Matrix
%Transition probability matrix, G=A+R

% Define species specific outgrowth matrices i.e. probability of moving into
next
%size class

A_acru=A_st;
A_bepa=A_it;
A_acsa=A_st;
A_fagr=A_st;
A_pist=A_mt;
A_pogr=A_it;
A_quru=A_mt;

A = blkdiag(A_acru,A_bepa,A_acsa,A_fagr,A_pist,A_pogr,A_quru,A_st,A_mt,A_it);
%outgrowth

%Define matrix for for existing tree effects on growth and sapling survival

R_acruacru=R_st_st; % effect of acru on acru
R_acrubepa=R_st; % effect of bepa on acru
R_acruacsa=R_st; % effect of acsa on acru
R_acrufagr=R_st; % effect of fagr on acru
R_acrupist=R_st; % effect of pist on acru
R_acrupogr=R_st; % effect of pogr on acru
R_acruquru=R_st; % effect of quru on acru
R_acrust=R_st; % effect of other st on acru
R_acrumt=R_st; % effect of other mt on acru
R_acruit=R_st; % effect of other it on acru

R_bepaacru=R_it; % effect of acru on bepa
R_bepabepa=R_it_it; % effect of bepa on bepa
R_bepaacsa=R_it; % effect of acsa on bepa
R_bepafagr=R_it; % effect of fagr on bepa
R_bepapist=R_it; % effect of pist on bepa
R_bepapogr=R_it; % effect of pogr on bepa
R_bepaquru=R_it; % effect of quru on bepa
R_bepast=R_it; % effect of other st on bepa
R_bepamt=R_it; % effect of other mt on bepa
R_bepait=R_it; % effect of other it on bepa

R_acsaacru=R_st; % effect of acru on acsa
R_acsabepa=R_st; % effect of bepa on acsa
R_acsaacsa=R_st_st; % effect of acsa on acsa
R_acsafagr=R_st; % effect of fagr on acsa
R_acsapist=R_st; % effect of pist on acsa
R_acsapogr=R_st; % effect of pogr on acsa
R_acsaquru=R_st; % effect of quru on acsa
R_acsast=R_st; % effect of other st on acsa
R_acsamt=R_st; % effect of other mt on acsa
R_acsait=R_st; % effect of other it on acsa

```



```

R_fagracru=R_st; % effect of acru on fagr
R_fagrbepa=R_st; % effect of bepa on fagr
R_fagracsas=R_st; % effect of acsa on fagr
R_fagrffagr=R_st_st; % effect of fagr on fagr
R_fagrpist=R_st; % effect of pist on fagr
R_fagrppogr=R_st; % effect of pogr on fagr
R_fagrqquru=R_st; % effect of quru on fagr
R_fagrst=R_st; % effect of other st on fagr
R_fagrmt=R_st; % effect of other mt on fagr
R_fagrfit=R_st; % effect of other it on fagr

R_pistacru=R_mt; % effect of acru on pist
R_pistbepa=R_mt; % effect of bepa on pist
R_pistacsas=R_mt; % effect of acsa on pist
R_pistffagr=R_mt; % effect of fagr on pist
R_pistfpist=R_mt_mt; % effect of pist on pist
R_pistppogr=R_mt; % effect of pogr on pist
R_pistqquru=R_mt; % effect of quru on pist
R_pistst=R_mt; % effect of other st on pist
R_pistmt=R_mt; % effect of other mt on pist
R_pistfit=R_mt; % effect of other it on pist

R_pogracsas=R_it; % effect of acru on pogr
R_pogrbepa=R_it; % effect of bepa on pogr
R_pogracsas=R_it; % effect of acsa on pogr
R_pogrfagr=R_it; % effect of fagr on pogr
R_pogrpist=R_it; % effect of pist on pogr
R_pogrpogr=R_it_it; % effect of pogr on pogr
R_pogrquru=R_it; % effect of quru on pogr
R_pogrst=R_it; % effect of other st on pogr
R_pogrmt=R_it; % effect of other mt on pogr
R_pogrfit=R_it; % effect of other it on pogr

R_quruacsas=R_mt; %effect of acru on quru
R_qurubepa=R_mt; % effect of bepa on quru
R_quruacsas=R_mt; % effect of acsa on quru
R_quruffagr=R_mt; % effect of fagr on quru
R_qurupist=R_mt; % effect of pist on quru
R_qurupogr=R_mt; % effect of pogr on quru
R_quruquru=R_mt_mt; % effect of quru on quru
R_qurust=R_mt; % effect of other st on quru
R_qurumt=R_mt; % effect of other mt on quru
R_qurufit=R_mt; % effect of other it on quru

R_stacsas=R_st; % effect of acru on other st
R_stbepa=R_st; % effect of bepa on other st
R_stacsas=R_st; % effect of acsa on other st
R_stffagr=R_st; % effect of fagr on other st
R_stfpist=R_st; % effect of pist on other st
R_stppogr=R_st; % effect of pogr on other st
R_stqquru=R_st; % effect of quru on other st
R_stst=R_st_st; % effect of other st on other st
R_stmt=R_st; % effect of other mt on other st
R_stfit=R_st; % effect of other it on other st

```

```

R_mtacru=R_mt; % effect of acru on other mt
R_mtbepa=R_mt; % effect of bepa on other mt
R_mtacsa=R_mt; % effect of acsa on other mt
R_mtfagr=R_mt; % effect of fagr on other mt
R_mtpist=R_mt; % effect of pist on other mt
R_mtpogr=R_mt; % effect of pogr on other mt
R_mtquru=R_mt; % effect of quru on other mt
R_mtst=R_mt; % effect of other st on other mt
R_mtmt=R_mt_mt; % effect of other mt on other mt
R_mtit=R_mt; % effect of other it on other mt

R_itacru=R_it; % effect of acru on other it
R_itbepa=R_it; % effect of bepa on other it
R_itacsa=R_it; % effect of acsa on other it
R_itfagr=R_it; % effect of fagr on other it
R_itpist=R_it; % effect of pist on other it
R_itpogr=R_it; % effect of pogr on other it
R_itquru=R_it; % effect of quru on other it
R_itst=R_it; % effect of other st on other it
R_itmt=R_it; % effect of other mt on other it
R_itit=R_it_it; % effect of other it on other it

R=[R_acruacru,R_acrubepa,R_acruacsa,R_acrufagr,R_acrupist,R_acrupogr,R_acruquru,
R_acrust,R_acrumt,R_acruit;

R_bepaacru,R_bepabepa,R_bepaacsa,R_bepafagr,R_bepapist,R_bepapogr,R_bepaquru,
R_bepast,R_bepamt,R_bepait;

R_acsaacru,R_acsabepa,R_acsaacsa,R_acsafagr,R_acsapist,R_acsapogr,R_acsaquru,
R_acsast,R_acsamt,R_acsait;

R_fagracru,R_fagrbepa,R_fagracsas,R_fagrffagr,R_fagrpist,R_fagrpogr,R_fagrquru,
R_fagrst,R_fagrmt,R_fagrit;

R_pistacru,R_pistbepa,R_pistacsa,R_pistfagr,R_pistpist,R_pistpogr,R_pistquru,
R_pistst,R_pistmt,R_pistit;

R_pogracru,R_pogrbepa,R_pogracsas,R_pogrfagr,R_pogrpist,R_pogrpogr,R_pogrquru,
R_pogrst,R_pogrmt,R_pogrit;

R_quruacru,R_qurubepa,R_quruacsa,R_qurufagr,R_qurupist,R_qurupogr,R_quruquru,
R_qurust,R_qurumt,R_quruit;

R_stacru,R_stbepa,R_stacsa,R_stfagr,R_stpist,R_stpogr,R_stquru,R_stst,R_stmt,
R_stit;

R_mtacru,R_mtbepa,R_mtacsa,R_mtfagr,R_mtpist,R_mtpogr,R_mtquru,R_mtst,R_mtmt,
R_mtit;

R_itacru,R_itbepa,R_itacsa,R_itfagr,R_itpist,R_itpogr,R_itquru,R_itst,R_itmt,
R_itit];

%Define transition probablity matrix,G
G=A+R;

```

```
%mortality vector = fraction of dying stems for each species/diameter class
mortal=zeros(length(s_t),1);
```

```
for i=1:(length(s_t)-1)
    mortal(i)=1-A(i,i)-A(i+1,i);
end
    mortal(length(s_t))=1-A(i,i);
```

```
%% Biomass
```

```
%Calculate initial biomass of stand using allometric equations
```

```
%constants for total aboveground biomass, source Perala and Alban 1994
```

```
%Acer rubrum
```

```
a_acru=0.1618;
```

```
b_acru=2.3095;
```

```
%Betula papyrifera
```

```
a_bepa=0.1182;
```

```
b_bepa=2.4287;
```

```
%Acer Saccharum
```

```
a_acsa=0.1957;
```

```
b_acsa=2.3916;
```

```
%Fagus grandifolia
```

```
a_fagr=0.1957;
```

```
b_fagr=2.3916;
```

```
%Pinus strobus
```

```
a_pist=0.0755;
```

```
b_pist=2.3833;
```

```
%Populus grandidentata
```

```
a_pogr=0.0785;
```

```
b_pogr=2.4981;
```

```
%Quercus rubra
```

```
a_quru=0.1335;
```

```
b_quru=2.422;
```

```
%Generic
```

```
a_gen=0.2471;
```

```
b_gen=2.4277;
```

```
A_vec(1:9)=a_acru;
```

```
A_vec(10:18)=a_bepa;
```

```
A_vec(19:27)=a_acsa;
```

```
A_vec(28:36)=a_fagr;
```

```
A_vec(37:45)=a_pist;
```

```
A_vec(46:54)=a_pogr;
```

```
A_vec(55:63)=a_quru;
```

```
A_vec(64:72)=a_gen;
```

```
A_vec(73:81)=a_gen;
```

```
A_vec(82:90)=a_gen;
```

```

B_vec(1:9)=b_acru;
B_vec(10:18)=b_bepa;
B_vec(19:27)=b_acsa;
B_vec(28:36)=b_fagr;
B_vec(37:45)=b_pist;
B_vec(46:54)=b_pogr;
B_vec(55:63)=b_quru;
B_vec(64:72)=b_gen;
B_vec(73:81)=b_gen;
B_vec(82:90)=b_gen;

med_DBH=[2.5;7.5;12.5;17.5;22.5;27.5;32.5;37.5;45]; %Assume a uniform
distribution within each size class
DBH=[med_DBH;med_DBH;med_DBH;med_DBH;med_DBH;med_DBH;med_DBH;med_DBH;med_DBH;
med_DBH];
AG_Biomass=((A_vec'.*power(DBH,B_vec')).*s_t)/1000; %biomass in Mg
or metric tonnes

AG_Biomass_sum=sum(AG_Biomass);

%% Carbon
%Calculate initial standing stock of C in tree biomass, woody debris, leaf
%litter, roots, root litter and soil organic matter

C_tree=0.5*AG_Biomass_sum; % Mg of C per hectare (source:Pregitzer and
Euskirchen 2004; Masera et al. 2003)
C_cwd=2.2; % Mg/ha source: Gough et al 2007 (UMBS pogr)
C_rts=C_tree*0.2; %Mg/ha (source: Roxburgh et al 2006 use 14%, Johnson et al
1995, Chater in McFee and Kelly, ed. p.482 23%)
C_rtlitt=C_rts*0.15; % Mg/ha source:Roxburgh et al 2006
C_lflitt=1.8; %Mg/ha source: Gough et al 2007 (UMBS pogr)
C_som=36; %Mg/ha (literature values: 104.1 Mg/ha source:Gough et al 2007
(UMBS pogr includes roots); 33 Mg/ha source:Pinard&Cropper 2000 (Asia
tropical); 125 Mg/ha source: Masera et al 2003 (European Douglas-fir and
Beech); 36-44 Currie et al 2003 (forest floor))

C_tot=C_tree+C_cwd+C_rts+C_rtlitt+C_lflitt+C_som; %total initial C

% decomposition constants
k_cwd=0.09; %decomposition constant for coarse woody debris (yr^-1) (source:
Gough et al 2007)
k_rtlitt=0.25; %decomposition constant for root litter (yr^-1)(source: Aber
et al 1990 (average of pist and acsa roots))
k_som=0.07; %decomposition constant for forest floor (yr^-1)(source: Currie
et al 2003)

k_lflitt_pogr=0.4; %decomposition constant for leaf litter (yr^-1)(source:
Gough et al 2007)
k_lflitt_acsa=0.38; %estimated based on averaged lignin concentrations from 4
sources
k_lflitt_acru=0.36; %estimated based on averaged lignin concentrations from 4
sources
k_lflitt_bepa=0.34; %estimated based on averaged lignin concentrations from 4
sources

```

```

k_lflitt_fagr=0.28; %estimated based on averaged lignin concentrations from 4
sources
k_lflitt_pist=0.32; %estimated based on averaged lignin concentrations from 4
sources
k_lflitt_quru=0.30; %estimated based on averaged lignin concentrations from 4
sources

```

```

%% Net Present Value

```

```

% Define discount rate (dr) for timber sale value

```

```

% dr=0.04;

```

```

% dr=0.1;

```

```

% dr=0.02;

```

```

dr=0;

```

```

% Assume cost of active management is equal to cost of passive management

```

```

% as harvest is carried out by outside company

```

```

% $/m3 average value from DNR sale data 1992-2005

```

```

p_m3_acru=[0;0;0;4.5;4.5;4.5;8;8;8]; % N Hardwood (acru,acsa, fagr)

```

```

p_m3_bepa=[0;0;0;6;6;6;6;6;6]; % Birch (bepa)

```

```

p_m3_acsa=[0;0;0;4.5;4.5;4.5;8;8;8]; % N Hardwood (acru,acsa, fagr)

```

```

p_m3_fagr=[0;0;0;4.5;4.5;4.5;8;8;8]; % N Hardwood (acru,acsa, fagr)

```

```

p_m3_pist=[0;0;0;8;8;8;8;8;8]; % White Pine (pist)

```

```

p_m3_pogr=[0;0;0;5.5;5.5;5.5;6;6;6]; % Aspen (pogr)

```

```

p_m3_quru=[0;0;0;5;5;5;7;7;7]; % Oak (quru)

```

```

p_m3_st=[0;0;0;0;0;0;0;0;0]; % Other st

```

```

p_m3_mt=[0;0;0;0;0;0;0;0;0]; % Other mt

```

```

p_m3_it=[0;0;0;0;0;0;0;0;0]; % Other it

```

```

% Build single price vectors for clearcut and partial cut ($/m^3)

```

```

p_m3=[p_m3_acru;p_m3_bepa;p_m3_acsa;p_m3_fagr;p_m3_pist;p_m3_pogr;p_m3_quru;p
_m3_st;p_m3_mt;p_m3_it];

```

```

% Parameters for allometric equations to get biomass (source: Clark and
Schroeder USDA FS 1986)

```

```

%Acer rubrum

```

```

a_acru_sw=0.05485;

```

```

b_acru_sw=1.21982;

```

```

%Betula papyrifera (used values for sweet birch)

```

```

a_bepa_sw=0.07232;

```

```

b_bepa_sw=1.15397;

```

```

%Acer Saccharum (used values for acru)

```

```

a_acsa_sw=0.05485;

```

```

b_acsa_sw=1.21982;

```

```

%Fagus grandifolia (used values for all species)

```

```

a_fagr_sw=0.03798;

```

```

b_fagr_sw=1.29756;

```

```

%Pinus strobus (used values for soft hardwoods)
a_pist_sw=0.03947;
b_pist_sw=1.29199;

%Populus grandidentata (used values for soft hardwoods)
a_pogr_sw=0.03947;
b_pogr_sw=1.29199;

%Quercus rubra
a_quru_sw=0.07170;
b_quru_sw=1.17986;

%Other (used values for all species)
a_gen_sw=0.03798;
b_gen_sw=1.29756;

A_vec_sw(1:9)=a_acru_sw;
A_vec_sw(10:18)=a_bepa_sw;
A_vec_sw(19:27)=a_acsa_sw;
A_vec_sw(28:36)=a_fagr_sw;
A_vec_sw(37:45)=a_pist_sw;
A_vec_sw(46:54)=a_pogr_sw;
A_vec_sw(55:63)=a_quru_sw;
A_vec_sw(64:72)=a_gen_sw;
A_vec_sw(73:81)=a_gen_sw;
A_vec_sw(82:90)=a_gen_sw;

B_vec_sw(1:9)=b_acru_sw;
B_vec_sw(10:18)=b_bepa_sw;
B_vec_sw(19:27)=b_acsa_sw;
B_vec_sw(28:36)=b_fagr_sw;
B_vec_sw(37:45)=b_pist_sw;
B_vec_sw(46:54)=b_pogr_sw;
B_vec_sw(55:63)=b_quru_sw;
B_vec_sw(64:72)=b_gen_sw;
B_vec_sw(73:81)=b_gen_sw;
B_vec_sw(82:90)=b_gen_sw;

% DBH (inches) for merchantable wood volume equations
DBH_in=DBH/2.54;

%% Management
H_year=1; %year of initial harvest
H_rp=50; %rotation period

Define harvest vectors for each species. (h is percent of stems harvested)
h_i=load('Harvest.txt');
h_acru=h_i(1:9,2);
h_bepa=h_i(10:18,3);
h_acsa=h_i(19:27,4);
h_fagr=h_i(28:36,5);
h_pist=h_i(37:45,6);
h_pogr=h_i(46:54,7);
h_quru=h_i(55:63,8);

```

```

% Build diagonal matrices for each species
H_acru=diag(h_acru);
H_bepa=diag(h_bepa);
H_acsa=diag(h_acsa);
H_fagr=diag(h_fagr);
H_pist=diag(h_pist);
H_pogr=diag(h_pogr);
H_quru=diag(h_quru);
H_st=diag(h_st);
H_mt=diag(h_mt);
H_it=diag(h_it);

% Build diagonal harvest matrix
H=blkdiag(H_acru,H_bepa,H_acsa,H_fagr,H_pist,H_pogr,H_quru,H_st,H_mt,H_it);

% Vectors for stand independent recruitment
c_acru=c_st;
c_bepa=c_it;
c_acsa=c_st;
c_fagr=c_st;
c_pist=c_mt;
c_pogr=c_it;
c_quru=c_mt;
c_ost=c_st;
c_omt=c_mt;
c_oit=zeros(9,1);

% Build single recruitment vector
c=[c_acru;c_bepa;c_acsa;c_fagr;c_pist;c_pogr;c_quru;c_ost;c_omt;c_oit];

```

```

%% Simulation
%Define length of simulation
n=200; %number of years to run

%define matrix to track size class history
s_t_hist=zeros((length(s_t)),n+1);
s_t_hist(:,1)=s_t; %first column is initial size class

%define matrices to track carbon history
C_hist=zeros(1,n+1);
C_hist(:,1)=C_tot; %first column is initial carbon in stand

C_hist_tree(:,1)=C_tree;
C_hist_cwd(:,1)=C_cwd;
C_hist_rts(:,1)=C_rts;
C_hist_rtlitt(:,1)=C_rtlitt;
C_hist_lflitt(:,1)=C_lflitt;
C_hist_som(:,1)=C_som;
C_hist_nosoil(:,1)=C_hist(:,1)-C_som(:,1);

C_h=zeros(1,n+1); % roots from harvested trees
C_lflitt_MX=zeros(n);

```

```

%define matrix to track biomass history
AG_Biomass_hist=zeros((length(s_t)),n+1);
AG_Biomass_hist(:,1)=AG_Biomass; %first column is initial biomass in stand
AG_Biomass_sum_hist=zeros(1,n+1);
AG_Biomass_sum_hist(:,1)=AG_Biomass_sum;%first column is summed initial
biomass in stand

%vector of annual leaf litter decomposition values
k_lflitt=zeros(1,n);

for i=1:n
    h_t=zeros(length (s_t),1);
    for j=0:n/H_rp
        if i==H_year+(j*H_rp)
            h_t=H*s_t; % harvest vector = %harvested * #stems
            continue
        end
    end

    s_t=G*(s_t-h_t)+c; % calculate new stems per hectare

    % algorithm for removing negative stem count
    for j=1:length(s_t)
        if s_t(j)<0
            s_t(j)=0;
        end
    end
    s_t_hist(:,i+1)=s_t;

    %Biomass
    AG_Biomass=(A_vec' .*power(DBH,B_vec')).*s_t/1000; %Mg/ha or tonnes/ha
    AG_Biomass_hist(:,i+1)=AG_Biomass;
    AG_Biomass_sum=sum(AG_Biomass);
    AG_Biomass_sum_hist(:,i+1)=AG_Biomass_sum;

    H_Biomass=(A_vec' .*power(DBH,B_vec')).*h_t/1000; % biomass of harvest
(Mg/ha)
    H_Biomass_sum=sum(H_Biomass); % sum of biomass harvest
    C_h(i+1)=0.2*(0.5*H_Biomass_sum); % C from harvested tree roots

    %Basal Area
    BA_vec=[B,B,B,B,B,B,B,B,B,B];
    BA_stand_hist=BA_vec*s_t_hist;

    BA_acru_hist=B*s_t_hist(1:9,:);
    BA_bepa_hist=B*s_t_hist(10:18,:);
    BA_acsa_hist=B*s_t_hist(19:27,:);
    BA_fagr_hist=B*s_t_hist(28:36,:);
    BA_pist_hist=B*s_t_hist(37:45,:);
    BA_pogr_hist=B*s_t_hist(46:54,:);
    BA_quru_hist=B*s_t_hist(55:63,:);
    BA_st_hist=B*s_t_hist(64:72,:);

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BA_mt_hist=B*s_t_hist(73:81,:);
BA_it_hist=B*s_t_hist(82:90,:);

% Diversity
s_t_d=s_t;
for k=1:length(s_t)
    if s_t_d(k)==0;
        s_t_d(k)=.00001; % ln(0) DNE
    end
    Diversity(k)=s_t_d(k)/sum(s_t_d)*log(s_t_d(k)/sum(s_t_d)); %
Shannon's Diversity Index
end
Diversity=-sum(Diversity);
Diversity_max=log(length(s_t));
Diversity_norm=Diversity/Diversity_max;
Diversity_hist(:,i)=Diversity_norm;

% Species and Size Diversity
rs_s_t_d=reshape(s_t_d,9,10);

for j=1:9
    for k=1:10

Diversity_sz(j)=(sum(rs_s_t_d(j,1:10)/sum(s_t_d)*log(sum(rs_s_t_d(j,1:10))/su
m(s_t_d))));

Diversity_sp(k)=(sum(rs_s_t_d(1:9,k)/sum(s_t_d)*log(sum(rs_s_t_d(1:9,k))/sum(
s_t_d))));
        end
    end
    Diversity_sp=-sum(Diversity_sp);
    Diversity_sz=-sum(Diversity_sz);
    Diversity_sp_max=log(10);
    Diversity_sz_max=log(9);
    Diversity_sp_hist(:,i)=Diversity_sp/Diversity_sp_max;
    Diversity_sz_hist(:,i)=Diversity_sz/Diversity_sz_max;

Harvest_Volume=((A_vec_sw'.*power(DBH_in.^2,B_vec_sw')).*(h_t))*3.62; %
convert inches to ft^3 to m^3
    Harvest_Volume_sum=sum(Harvest_Volume);
    SV(i)=Harvest_Volume'*p_m3; % Stand Value at time i equals the
merchantable volume of the harvest * price per m^3
    NPV(i)=SV(i)/((1+dr)^i); % NPV=Net Present Value
    NPV_sum(i)=sum(NPV);

%vector of k values
AGB_species=[sum(AG_Biomass_hist(1:9)); sum(AG_Biomass_hist(10:18));
sum(AG_Biomass_hist(19:27)); sum(AG_Biomass_hist(28:36));
sum(AG_Biomass_hist(37:45));sum(AG_Biomass_hist(46:54));sum(AG_Biomass_hist(5
5:63));sum(AG_Biomass_hist(64:72));sum(AG_Biomass_hist(73:81));sum(AG_Biomass
_hist(82:90))];
    Dominant=max(AGB_species);

if Dominant==AGB_species(1)
    k_lflitt(i)=k_lflitt_acru;

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    else if Dominant==AGB_species(2)
k_lflitt(i)=k_lflitt_bepa;
    else if Dominant==AGB_species(3)
k_lflitt(i)=k_lflitt_acsa;
    else if Dominant==AGB_species(4)
k_lflitt(i)=k_lflitt_fagr;
    else if Dominant==AGB_species(5)
k_lflitt(i)=k_lflitt_pist;
    else if Dominant==AGB_species(6)
k_lflitt(i)=k_lflitt_pogr;
    else if Dominant==AGB_species(7)
k_lflitt(i)=k_lflitt_quru;
    else if Dominant==AGB_species(8)
k_lflitt(i)=k_lflitt_acsa;
    else if Dominant==AGB_species(9)
k_lflitt(i)=k_lflitt_quru;
    else if Dominant==AGB_species(10)
k_lflitt(i)=k_lflitt_pogr;
        end
        end
        end
        end
        end
        end
        end
        end
        end
        end
end

% Carbon
C_tree=0.5*AG_Biomass_sum_hist(i);
C_rts=0.2*C_tree;

% vector of new leaf litter input
C_lflittNEW(i)= 0.47*0.0125*AG_Biomass_sum; % Johnson et al 1995,
Chapter in McFee and Kelly, ed. p.482, leaf litter is 45% C

% vector of new cwd input (all dead stems >10cm DBH biomass)
mortal_B=mortal.*(0.95*AG_Biomass);
C_cwdNEW(i)= sum(mortal_B)*0.50; % 50% of dead biomass is C

for j=1:n
    if i==j
        C_lflitt_MX(j,i)=C_lflittNEW(i);
    else if i>j
        C_lflitt_MX(j,i)=0;
    else if i<j
        C_lflitt_MX(j,i)=C_lflitt_MX(i,i)*exp(-k_lflitt(i)*j);

        end
    end
end
end
C_lflitt=sum(C_lflitt_MX(i,:));

```

```

if i>1
    C_lflitt_decay=C_lflitt-sum(C_lflitt_MX(i-1,:));
else
    C_lflitt_decay=0;
end

C_som=C_som-
(C_som*k_som)+(0.43*(C_lflitt_decay+(C_cwd*k_cwd)))+(1*C_rtlitt*k_rtlitt); %
0.43=humification fraction (source: Roxburgh et al 2006)

C_rtlitt=C_rtlitt+C_h(i)+(C_rts*0.026)-(C_rtlitt*k_rtlitt); % Value
for new rtlitt from Johnson et al 1995, Chapter in McFee and Kelly, ed. p.482
C_cwd=C_cwd+C_cwdNEW(i)-(C_cwd*k_cwd);

C_tot=C_tree+C_cwd+C_rts+C_rtlitt+C_lflitt+C_som;
C_nosoil=C_tree+C_cwd+C_rts+C_rtlitt+C_lflitt;

C_hist(:,i+1)=C_tot;
C_hist_tree(:,i+1)=C_tree;
C_hist_cwd(:,i+1)=C_cwd;
C_hist_rts(:,i+1)=C_rts;
C_hist_rtlitt(:,i+1)=C_rtlitt;
C_hist_lflitt(:,i+1)=C_lflitt;
C_hist_som(:,i+1)=C_som;
C_hist_nosoil(:,i+1)=C_nosoil;

C_flux(i)=C_hist(:,i+1)-C_hist(:,i);
C_flux_nosoil(i)=C_hist_nosoil(:,i+1)-C_hist_nosoil(:,i);

p_C=4.5; % assume a tonne of C trades for $4.50
C_value=C_tot*p_C; %Get value of carbon stored

C_net_hist(i)=sum(C_flux); % net change in C storage (Mg/ha)
end

C_net=sum(C_flux); % net change in C storage (Mg/ha)

```