Modeling of Silvicultural Treatments: Impacts on Oak Regeneration and Carbon Sequestration

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Abstract

Our study applied system dynamics modeling to evaluate silvicultural treatment impacts on oak regeneration and carbon sequestration in upland hardwood forest of Mississippi. Using STELLA Architect software, we simulated three management scenarios over 20 years: control (no intervention), moderate thinning (30% basal area reduction), and intensive thinning (50% basal area reduction). Results revealed distinct trade-offs between oak recruitment and carbon storage. Moderate thinning enhanced oak recruitment by ~15% compared to control while maintaining carbon storage recovery to baseline level within 10 years. Intensive thinning produced the strongest recruitment response (30% above control) but incurred substantial short-term carbon loss (~25%) with extended recovery period. Sensitivity analysis across three growth and mortality scenarios confirmed model robustness, demonstrating consistent treatment response patterns under varying ecological conditions. The findings suggest moderate thinning provides an optimal balance for multi-objective forest management, supporting both biodiversity conservation and carbon sequestration goals. This system dynamics approach offers a valuable decision-support tool for sustainable forest management under changing environmental conditions.

Keywords: System dynamics, forest management, carbon sequestration, oak regeneration, ecological modeling, silviculture

Introduction

Upland hardwood forests characterized by oaks, hickories, pines, and other hardwoods are environmentally, culturally, and commercially significant; and require successful regeneration, particularly of oak species to support biodiversity and ecosystem functions (Figure 1) (Ibeh et al., 2024a). However, these forests face major challenges in oak recruitment caused by historical fire suppression, shifts in past land-use, increased competition from shade-tolerant species and deer browsing (Nowacki & Abrams, 2008; Brose et al., 2013; Loftis, 1990). The regeneration crisis threatens the composition of forests and their ability to store carbon, which creates a conflict between immediate need for oak recruitment and long-term goals of keeping carbon reserves. Despite the many silvicultural interventions implemented to alleviate these issues, such as prescribed fire, thinning, and shelterwood harvests, regeneration outcomes remain variable and often limited (Brose et al., 1998; Clatterbuck & Armel, 2010; Dey et al., 2016; Iverson et al., 2008; Loftis, 1990). In this study, we applied system dynamics modeling approach to evaluate the long-term impacts of silvicultural interventions on oak regeneration and carbon sequestration in the upland hardwood forest of Mississippi.

Figure 1. Ecological diversity and ecosystem functions of upland hardwood forest (Ibeh et al., 2024b)

Methods

Model description and setup

We developed system dynamic model (Figure 2) using STELLA Architect software (isee systems, 2023) to estimate how moderate and intensive thinning treatments affect oak regeneration and carbon storage over a 20-year simulation period. We calibrated the model to a time step of 22.8 days (delta time (DT) = 0.0625), which was selected to balance computational efficiency with simulation smoothness.

The model combines essential forest processes such as growth, mortality, recruitment, light availability, and carbon dynamics across interconnected components. Carbon sequestration in the forest is represented by biomass accumulation equations that incorporate photosynthetic carbon uptake, carbon allocation to woody tissues and carbon losses caused by respiration and mortality. Light availability incorporates canopy closure effects on understory conditions, which directly influence oak seedling establishment and survival rates.

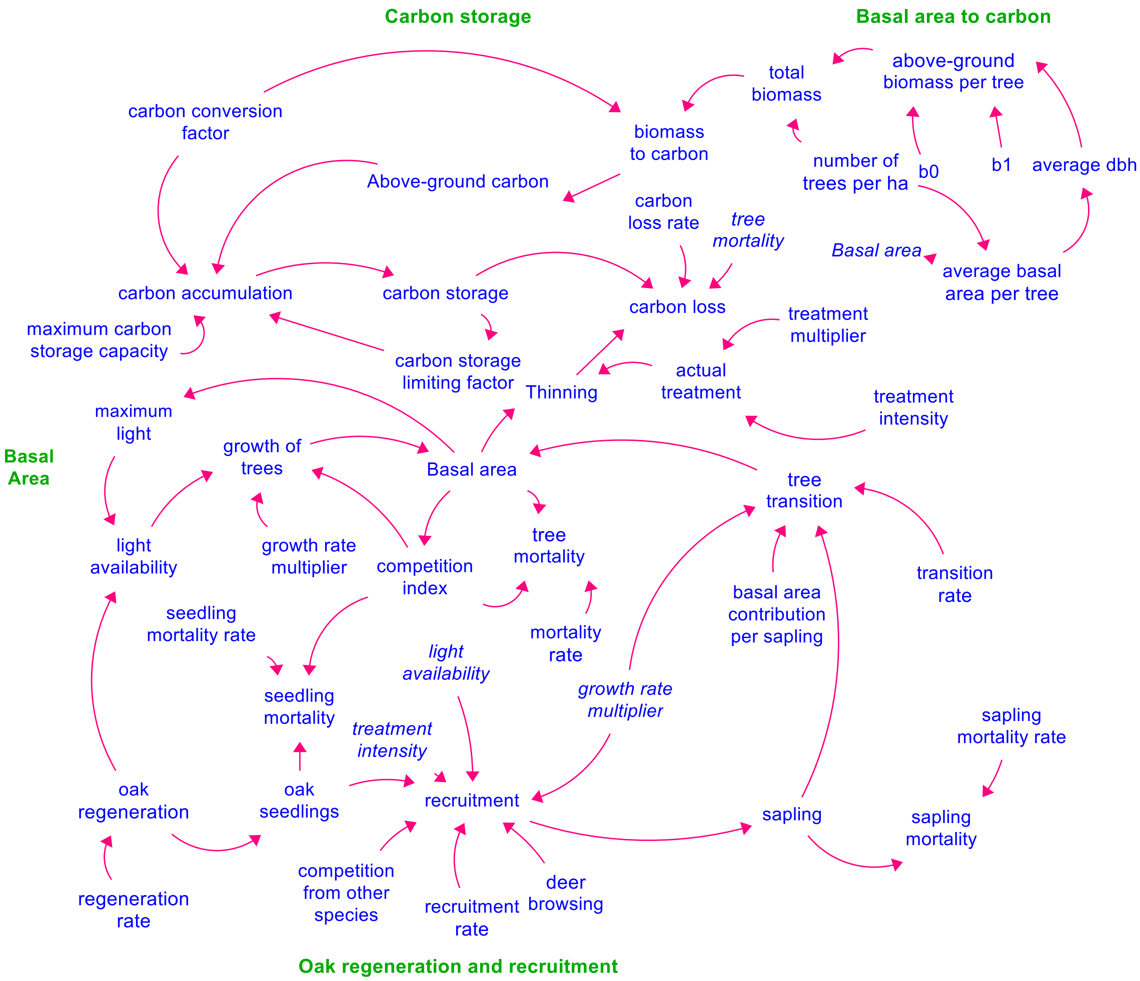

Figure 2. Causal loop for the model oak recruitment and carbon storage (A complete Stock-Flow Diagram showing detailed model structure with stocks, flows, and mathematical relationships will be provided in future publications).

Treatment Scenarios

Three management scenarios were implemented following Ibeh et al. (2024a):- control (no intervention), moderate thinning (30 % reduction in residual basal area), and intensive thinning (50% reduction in residual basal area). All treatments were administered in the fifth year of simulation to allow baseline establishment and clear comparison of treatment effects. We calibrated the model parameters using empirical data from upland hardwood forests in Mississippi (Ibeh et al., 2024a) and added data from similar ecosystems in the southeastern United States (Brose et al., 2013; Dey & Schweitzer, 2014; Loftis, 1990; Nowacki & Abrams, 2008; Schweitzer & Dey, 2011: Schweitzer et al., 2016).

Biomass conversion factors were held constant throughout simulation. Aboveground biomass was calculated using established allometric equations (Chojnacky et al., 2014; Jenkins et al., 2003). We did some assumptions for our model such as (1) uniform environmental conditions across the study area and (2) exclusion of stochastic disturbances such as pests, extreme weather events, or wildfire to focus specifically on silvicultural treatment effects.

Sensitivity Analysis Methods

We conducted sensitivity analyses to assess the model robustness across different growth and mortality conditions. We tested three parameter scenarios for each treatment: Scenarios (1) low growth rate (5 %/year) and high mortality rate (2 %/year), (2) moderate growth rate (10 %/year) and moderate mortality rate (1 %/year), and (3) high growth rate (15 %/year) and low mortality rate (0.5 %/year). This approach allows systematic exploration of the complex interactions between forest structure, recruitment dynamics and carbon sequestration under different management regimes while providing quantitative measures of model responsiveness to parameter uncertainty.

Preliminary results

Treatments produced distinct forest recovery patterns (Figure 3). Control treatment kept steady carbon stocks and basal area but exhibited minimal oak recruitment due to limited light penetration (Figure 3A). Moderate thinning improved trade-offs and enhanced oak recruitment (~15% compared to control) whereas recovering carbon storage to baseline levels within 10 years (Figure 3B). The treatment created an initial decline in both basal area and carbon storage at year 5, followed by gradual recovery as remaining trees responded to reduced competition.

Intensive thinning produced the most dramatic response patterns (Figure 3C). Though this treatment initially improved recruitment (30% above control) through aggressive canopy removal, it incurred substantial short-term carbon loss (~25%) with delayed recovery extending beyond year 15. The more intensive biomass removal created longer-lasting structural changes, retaining elevated light conditions but requiring extended time for carbon stock recovery.

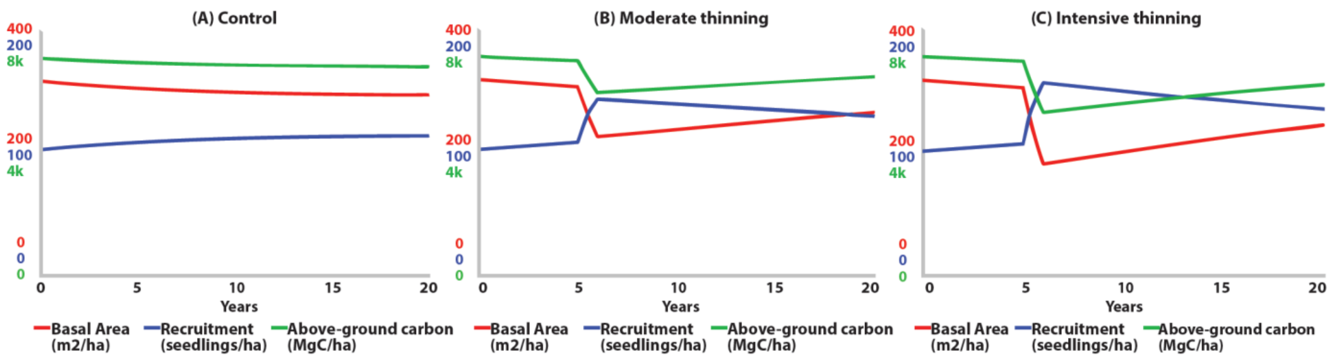

Figure 3. Trends in oak recruitment, basal area, and carbon over time

Sensitivity analysis confirmed pattern robustness across ecological conditions while revealing important parameter interactions (Table 1). Under stressed conditions (Scenario 1: low growth/high mortality), all treatments showed higher recruitment but slowed basal area recovery and reduced carbon storage. On the contrary, Scenario 3 (high growth/low mortality) which represented an optimum condition demonstrated accelerated basal area recovery and increased carbon storage; however, recruitment was reduced. Possibly due to faster canopy closure limiting light availability.

The differences among treatment became most apparent under Scenario 2 (moderate condition). Control maintained balanced carbon storage and reduced recruitment. The 30% reduction in basal area achieved moderate recruitment and balanced carbon storage. Intensive thinning produced higher recruitment but suffered significantly reduced carbon storage; thus highlighting the trade-offs between improved recruitment and carbon retention. These consistent patterns across scenarios confirm our models ability to capture fundamental ecological relationships under varying environmental conditions.

Table 1. Summary of sensitivity analysis results under different growth and mortality rates

Treatment	Scenario	Parameter	Basal area (recovery)	Carbon storage (accumulation)	Recruitment
Control	1	Low GR (5%/yr) and high MR (2%/yr)	Slowed	Reduced	Higher
	2	Moderates GR (10%/yr) and MR (1%/yr)	Steady	Balanced	Reduced
	3	High GR (15%/yr) and low MR (0.5%/year)	Accelerated	Increased	Reduced

Moderate thinning	1	Low GR (5%/yr) and high MR (2%/yr)	Slowed	Reduced	Higher
	2	Moderates GR (10%/yr) and MR (1%/yr)	Steady	Balanced	Moderate
	3	High GR (15%/yr) and low MR (0.5%/year)	Accelerated	Increased	Reduced
Intensive thinning	1	Low GR (5%/yr) and high MR (2%/yr)	Slowed	Reduced	Higher
	2	Moderates GR (10%/yr) and MR (1%/yr)	Slowed	Significantly reduced	Higher
	3	High GR (15%/yr) and low MR (0.5%/year)	Accelerated	Increased	Reduced

Where GR = growth rate, MR = mortality rate, and yr is the year.

Discussion

Our study demonstrates system dynamics modeling as a valuable decision-support tool for forest management. System dynamics models are particularly effective since they integrate multiple ecological processes, incorporate feedback loops, and allow exploration of dynamic trade-offs across spatial and temporal scales (Sacchelli, 2018; Vanclay, 2014). At the same time, ecological silviculture emphasizes the importance of balancing competing management objectives, such as sustaining biodiversity, timber production, and carbon storage within complex forest systems (Palik et al., 2021). By putting together these perspectives, our approach captured the temporal dynamics of silvicultural interventions, revealing emergent patterns that would be difficult to detect through traditional experimental methods.

Moderate thinning emerge as the sustainable strategy for multi-use landscapes, balancing carbon storage with biodiversity and regeneration goals. This aligns with payments for ecosystem services (PES) frameworks incentivizing many environmental benefits (Dey, 2014; Fripp, 2014; Wunder, 2015). Results encourage evidence-based climate adaptation strategies that support carbon sequestration while enhancing ecological resilience (Griscom et al., 2017). This approach is especially relevant in the context of climate change where forests are key to mitigating carbon emissions as well as maintaining ecological resilience (Ryan et al., 2010).

Limitations and Future Research

This study has some limitations. The model centered on aboveground carbon pools and does not incorporate soil carbon dynamics, which represent a significant component of forest carbon storage. Also, the model does not account for prescribed fire impacts, recurring silvicultural treatments, or implementation emissions associated with forest management activities. The model currently employs generalized parameters rather than species-specific coefficients and does not simulate stochastic disturbances or long-term species interactions that could influence forest carbon dynamics.

Future research will address these limitations via (1) model validation using independent datasets (e.g. Forest Inventory and Analysis (FIA) data); and comprehensive goodness-of-fit analyses. Subsequent efforts will (2) incorporate species-specific parameters, and simulate longer-term species interactions. Our priorities will include to (3) refine stochastic disturbance assumptions, improve biomass conversion factors, as well as tackle parameter variability to enhance applicability in diverse ecosystems.

Conclusion

This study demonstrates that system dynamics modeling provides a robust framework for estimating complex trade-offs in forest management decisions. Our 20-year simulations revealed that moderate thinning offers adequate balance between oak regeneration improvement vs. carbon storage maintenance (recovery of both basal area and carbon stocks within the simulation period). In contrast, intensive thinning maximizes short-term recruitment gains; but take longer time to recover carbon.

The sensitivity analysis confirms these patterns hold across different ecological conditions, with oak recruitment showing highest responsiveness to light availability changes. Overall, our findings support evidence-based forest management strategies that can simultaneously address biodiversity conservation, and climate mitigation goals. As forest managers are increasingly under pressure to achieve many ecosystem services, system dynamics modeling provides valuable decision-support system to navigate complex silvicultural choices under changing environmental conditions.

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