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CONIFER RETENTION AND HARDWOOD MANAGEMENT AFFECT INTERPLAY BETWEEN HARVEST VOLUME AND CARBON STORAGE OVER 100 YEARS IN DOUGLAS-FIR/TANOAK: A CASE STUDY

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ABSTRACT. Modern forest management involves tradeoffs between harvest intensity and carbon storage in live trees. A key component is how non-merchantable tree species are treated. We simulated forest growth and yield over a century of multiaged management in a mixed stand in northern California. Pre-treatment basal area comprised 136 ft² ac⁻¹ (31 m² ha⁻¹) non-merchantable hardwood and 73 ft² ac⁻¹ (17 m² ha⁻¹) merchantable conifer. Individual-tree selection harvest was simulated for various conifer BA retention levels at 20-year harvest return intervals. Silvicultural prescriptions promoted conifer dominance by retaining only 5 ft² ac⁻¹ (1.1 m² ha⁻¹) hardwood BA at each harvest. Alternatively, retaining 50% of hardwood BA at each harvest slowed the conversion to conifer dominance. Higher BA retention favored per-acre growth and storage of carbon in live trees. Lower BA retention sacrificed per-acre wood volume growth, but sizeable early conifer harvests ensued. The FORSEE growth and yield model did not predict the expected positive responses of conifer tree growth to treatments that eliminated hardwoods, suggesting it may not adequately simulate benefits of hardwood management. Therefore, our projections of growth and harvest yield should be regarded as conservative when evaluating forest restoration and management options in terms of growth, yield, and carbon dynamics.

Keywords: Carbon sequestration, forest carbon, FORSEE, hardwood sprouting, multiaged management, partial harvesting, uneven-aged silviculture, variable retention.

1 INTRODUCTION

Forest management and restoration of conifer dominance has the potential to offset greenhouse gas (GHG) emissions via enhanced carbon sequestration and storage in healthy, resilient, fire-resistant, productive, conifer-dominated forests (Berrill and Han 2017). Reducing GHGs to 1990 levels statewide by the year 2020 is the primary objective of the California Global Warming Solutions Act of 2006 (AB 32). We expect forest carbon projects to provide GHG emission reduction benefits via timber harvesting to produce long-lived solid-wood products that store carbon instead of letting trees in overstocked stands die, decay, and release carbon to the atmosphere. We also expect GHG emission reduction benefits by retaining higher rates of forest growth and carbon sequestration by returning species composition to the more productive historical conditions where fast-growing, long-lived conifers dominated. High trans-

action costs may prevent smaller landowners from entering carbon markets (Jenkins 2018; Kelly and Schmitz 2016), but all landowners should understand how their management decisions affect carbon dynamics and how they might enhance carbon sequestration and storage in trees.

1.1 Restoring conifer dominance

California's Coast Range has forests dominated by redwood (*Sequoia sempervirens*) towards the coast, and drier upland forests located further inland that were once dominated by coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). These upland forests have been harvested one or more times, with reforestation generally favoring re-sprouting hardwoods such as tanoak (*Notholithocarpus densiflorus*) that reoccupy the site more consistently than naturally-regenerating Douglas-fir seedlings (Tappeiner et al. 2007). Tanoak competi-

tion impacts the growth of Douglas-fir (Devine and Harrington 2008; Harrington and Tappeiner 2009) and forest productivity overall (Berrill and O'Hara 2014, 2016). Tanoak also creates a potential forest health risk via disease and wildfire risk (Varner et al. 2017).

There is disagreement on how to best mitigate tanoak's impact on the maintenance of conifers stocking levels; whether tanoak trees should be eliminated completely, or partially, using herbicides, or cut and allowed to re-sprout from cut stumps. If conifer growth could be enhanced by only removing a small portion of the hardwood competition, landowners would enjoy reduced treatment costs and other benefits of maintaining a hardwood component such as wildlife habitat and mast production (Raphael 1987), and post-disturbance slope stabilization coming from root systems that re-sprout (Stokes et al. 2009). Hardwood removal also has the potential to alter forest carbon dynamics and fire behavior. Herbicide-killed tanoak that remain standing will decay, break down, and fall gradually. Conversely, cut tanoak that are not extracted from the forest instantly become surface fuels, and we expect their re-sprouting stumps to transition from patchy surface fuels into vertical ladder fuels as they grow taller (Sugihara 2006, Valachovic et al. 2011; Forrestel et al. 2015). Resprouting hardwoods can be sprayed or prevented from re-sprouting using cut stump treatments (Ashton and Kelty 2018), but the most cost-efficient method of hardwood removal is to kill standing trees by stem-injection frill treatment (Caffereta and Yee 1991). Efficacy of frill treatments improved with the introduction of imazapyr (Minogue 1997).

There is interest in restoring conifer dominance in these Coast Range forests, but low conifer stocking and other factors such as remoteness from forest products processing facilities reduce income and profit from timber harvesting that are needed to fund treatments. Additional sources of income supplementing or replacing timber revenue may give landowners flexibility to accomplish restoration goals without resorting to heavy cutting. For example, sale of carbon offsets predicated on maintaining higher stand density could fund the reduction in tanoak density and planting of conifer seedlings in the understory. The income from carbon sales may allow landowners to reduce or defer their conifer harvesting activities in the near term, allowing them to maintain higher stand densities and therefore enhance per-acre forest growth (Oliver and Larson 1996; Berrill and Han 2017).

1.2 Carbon vs. timber revenues

The advent of forest carbon projects in California raises questions about tradeoffs between management

for timber and ecosystem services such as carbon storage over long time horizons. Of particular interest is how stand density and species composition affect this tradeoff. Answering these questions requires long-term future projections from forest growth and yield models. We use model output (yield tables) and other allometric equations and conversion factors to estimate forest product yields and carbon sequestration and storage services (Bettinger et al. 2009; Malmshiemer et al. 2011). Consideration of economics and capital budgeting makes heavier earlier cutting for timber revenue appear favorable, particularly when discount rates are high. However, the potential revenue stream coming from carbon sequestration and storage may be compromised, since stands with lower densities (fewer trees) sequester less carbon per acre. Additionally, heavier cutting of merchantable tree species leaves fewer of these trees to accrue volume for future harvests. Thus, the need is for a projection of forest growth and yield under different silvicultural regimes to describe the tradeoffs between forest products and services, and how this might change over time, among forests with different structure and composition (Weiskittel et al. 2011).

Reliably quantifying GHG emission reduction benefits over long time periods is challenging. One requirement of California's AB 32 Global Warming Solutions Act is that carbon projects demonstrate GHG emission reductions that are real, permanent, quantifiable, verifiable, and enforceable by the state board. Forest growth and yield modeling must be verified by repeatedly collecting forest monitoring data. These data also have value for forest inventory and appraisal, and to validate or calibrate growth and yield models. There is considerable uncertainty associated with the current growth and yield model projections of change under different forest management prescriptions over extended periods (Melson et al. 2011). In addition, more variable contemporary management prescriptions may not be well represented in the data used to develop existing models (D'Amato et al. 2017). For example, Berrill et al. (2012) showed how multiaged redwood responded to lower stand densities with greater dbh growth but not height growth, leading to lower height:diameter ratios (greater stem taper). This affects log volumes and the production of sawn timber. In addition to positive dbh growth response to partial harvesting, herbicide control of competing hardwood in the vicinity of redwood also led to a pronounced dbh growth response (Howe 2014). Berrill and O'Hara (2016) demonstrated how multiaged redwood altered rates of height or diameter growth independently according to different biophysical factors that are not accounted for in growth and yield models. However, in the absence of long-term datasets covering a wide range of management scenarios, we must rely on growth and yield models to

quantify production and services, and compare different approaches to forest management.

The goal of this simulation study was to quantify products and services derived from different multiaged management approaches to restoring conifer dominance in unmanaged naturally-regenerated forests. Our specific objectives were to examine the influence of different conifer retention scenarios and different treatments controlling competing hardwoods on stand growth, harvest volumes, and carbon storage with partial harvesting on a 20 year cutting cycle over a 100-year modeling period. We modeled conifer harvests and carbon storage in live trees and sawn timber, and how these changed over time. Prescriptions were designed to reestablish conifer dominance by preferentially cutting hardwoods, and promoting natural regeneration of merchantable conifers through partial harvest disturbances. We also developed “no conifer harvest” scenarios which involved cutting or culling hardwood with herbicide without any conifer harvest (avoiding operational and permitting costs associated with timber harvesting), and a no-treatment benchmark against which to compare all other treatments. We hypothesized that growth and yield responses understood through the results of field-based studies on stand density management and treatment response would be adequately represented in the predicted outcomes of various simulations.

2 METHODS

2.1 Growth and yield modeling

To generate estimates of basal area (BA) development, harvest yields, and carbon dioxide equivalent (CO_2e) in live biomass and sawn timber, forestry students at Humboldt State University used FORSEE (Build.26, released February 2015) to model stand growth, yield, and carbon. FORSEE is a growth and yield model approved by the California Air Resources Board for carbon offset projects (<http://www.arb.ca.gov>). The distance-independent individual-tree model allows users to simulate growth and yield of pure and mixed even-aged and multiaged stands of species native to California’s Coast Range. The model restricts growth of trees and regeneration according to a competition factor based on canopy cover from trees with crowns of similar or higher stature. We used stand data representative of unmanaged stands on relatively poor sites throughout the Coast Range (mixed conifer-hardwood, dominated by tanoak and Douglas-fir) and relatively low site class (Douglas-fir site index 114 ft (35 m) at base age 50 yrs) to represent the pretreatment condition (FORSEE Stand DR3D.41). The 18-acre (7.3 ha) stand was represented by four plots with individual tree growth mod-

eled separately within each plot then aggregated into one yield table.

Multiaged management on private land along the north coast of California involves marking timber for harvest according to a silvicultural prescription such as “retain $X \text{ ft}^2 \text{ ac}^{-1}$ conifer BA, and do Y with hardwood”. The students simulated stand growth and harvests on a 20-year cutting cycle over 100 years, for a range of residual conifer densities (in terms of conifer BA retained). Each student was assigned one conifer retention level: BA 40, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, or $200 \text{ ft}^2 \text{ ac}^{-1}$ and two hardwood retention scenarios: retain $5 \text{ ft}^2 \text{ ac}^{-1}$ hardwood BA or retain 50% of hardwood BA (i.e., retain every other hardwood). Cull hardwoods were either cut and re-sprouted, or killed with herbicide (no re-sprouting) for comparison. The hardwood treatments were simultaneously scheduled to coincide with the individual-tree selection conifer harvests. We assumed this disturbance resulted in natural regeneration of 30 tpa (74 stems ha^{-1}) Douglas-fir, and re-sprouting of cut hardwoods in some scenarios. For comparison, each student simulated a no-cut, no-treatment control, and a no-cut chemical-only control of hardwoods in the “chemical only” treatment simulated in FORSEE by thinning to leave $5 \text{ ft}^2 \text{ ac}^{-1}$ hardwood without cutting any conifer, then growing the (now conifer-dominated) residual stand for 100 years.

We made the following assumptions with respect to modeling harvesting and regeneration with FORSEE: harvest treatments were applied at the beginning of 5-yr modeling time-steps; sprout regeneration was set to zero to reflect planned application of herbicides to unwanted hardwood; Douglas-fir seedlings were introduced into model runs after each stand entry. FORSEE harvest routine settings focused cutting on hardwood trees or conifer trees with the lowest crown ratio. Other default model values were used for seedling and sprout regeneration.

2.2 Carbon calculations

The students copied yield tables into a spreadsheet where we converted cubic stemwood volume per acre predicted using FORSEE into pounds by applying a factor of 26.77 for conifer (Douglas-fir) and 30.14 for hardwoods (mainly tanoak) (California Air Resources Board 2015). We converted pounds to metric tons using a factor of 0.000453592 and CO_2e using factor 1.8333, ignoring possible but unknown variations in wood density and carbon fraction between prescriptions (Jones and O’Hara 2012). We then converted mass of the stemwood component into total aboveground biomass (AGB) according to tree size using the stemwood biomass ratio equations of Jenkins et al. (2003) for conifer =

$\exp(-0.3737 - 1.8055/(dbh \times 2.54))$ and hardwood = $e(-0.3065 - 5.424/(dbh \times 2.54))$. Next we averaged metric tons per acre of CO₂e stored above ground in live trees for each 20-yr period between harvest treatments (e.g., at time 0, 5, 10, 15, and 20 yrs) throughout the 100-yr modeling period.

By applying regional mill efficiency data for north coastal California softwoods ($\times 0.675$) to CO₂e in cubic harvested stemwood volumes, we divided this carbon pool into 67.5% wood products and 32.5% sawmill residues. We adjusted the wood product volume ($\times 0.97$) to reflect regional recovery rate of 97% in long-lived solid-wood lumber products (Regional Mill Efficiency Data.xls and Harvested Wood Products worksheet in Area Assessment Data File.xls; www.arb.ca.gov/cc/capandtrade/protocols/usforest/usforestprojects.2015.htm).

2.3 Pre-treatment conditions

Before harvest in Year 0, the young stand had BA of 209 ft² ac⁻¹ (50 m² ha⁻¹) (all species), but only had 73 ft² ac⁻¹ (17 m² ha⁻¹) conifer BA. The conifers out-sized the hardwoods, with 13.8 in (35 cm) quadratic mean diameter (qmd) for conifers (70 tpa; 173 stems ha⁻¹) versus only 5.0 in (12.7 cm) qmd for hardwoods (1013 tpa; 2675 stems ha⁻¹). Hardwoods outnumbered conifers >14:1. Stand density index (SDI) for all species combined was 454 (1121 metric) or 76% of maximum SDI for Douglas-fir (Reineke 1933). Standing volume was 11.7 MBF ac⁻¹ with the majority (10.4 MBF ac⁻¹) being conifer volume. Site index for Douglas-fir was 114 ft at base age 50 years, which is at the high end of the range for site class III (King 1966; Krumland and Eng 2005).

3 RESULTS

3.1 Conifer basal area retention

Since hardwoods dominated the pre-treatment stand, there were few conifers available for harvest. In year 0, conifer harvesting could only be performed when prescriptions called for retention below the pre-treatment conifer BA of 73 ft² ac⁻¹ (Figure 1). At the next harvest, in year 20, conifers had grown, allowing for more conifer harvesting. However, only in year 40 was there enough conifer BA to allow for harvesting under prescriptions with relatively high conifer retention. In the absence of conifer harvests, prescriptions with high conifer retention only allowed for hardwood treatments. Total harvest volume summed over 100 years was maximized at conifer retention levels around 60–80 ft² ac⁻¹ (14–18 m² ha⁻¹) BA. Above these levels of conifer retention, a steady increase in carbon storage in live trees and long-

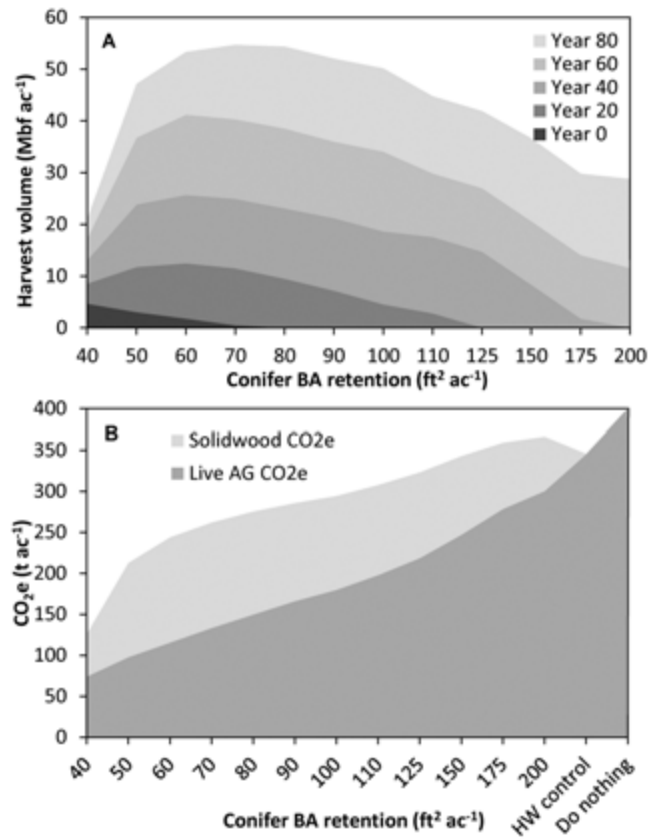


Figure 1: Harvest volumes (thousand board feet; MBF) (A) and 100-year average carbon storage in live trees and long-lived solid-wood products (B) according to conifer retention at 20-year harvest intervals, assuming retention of 5 ft² ac⁻¹ hardwood at each harvest, no hardwood sprouting (chemical control of hardwood), and 30 tpa Douglas-fir natural seedling regeneration after each harvest. Note: unequal intervals of BA retention on x-axis.

lived solid-wood products came at the expense of harvest volume in years 0 and 20. Conversely, with conifer retention below 50 ft² ac⁻¹ (11 m² ha⁻¹) stand BA was so low that 100-year harvest volume and carbon storage fell sharply (Figure 1).

3.2 Rate of conversion to conifer dominance

Removing all but 5 ft² ac⁻¹ hardwood BA at each entry quickly left the residual stand in a conifer-dominated state. Conversely, the gradual conversion achieved by only removing/retaining 50% of hardwood BA at each conifer harvest enhanced live tree CO₂e storage versus when only 5 ft² ac⁻¹ of hardwood was retained at each entry over the 100-year modeling period (Figure 2A). This pattern was reversed when comparing harvest vol-

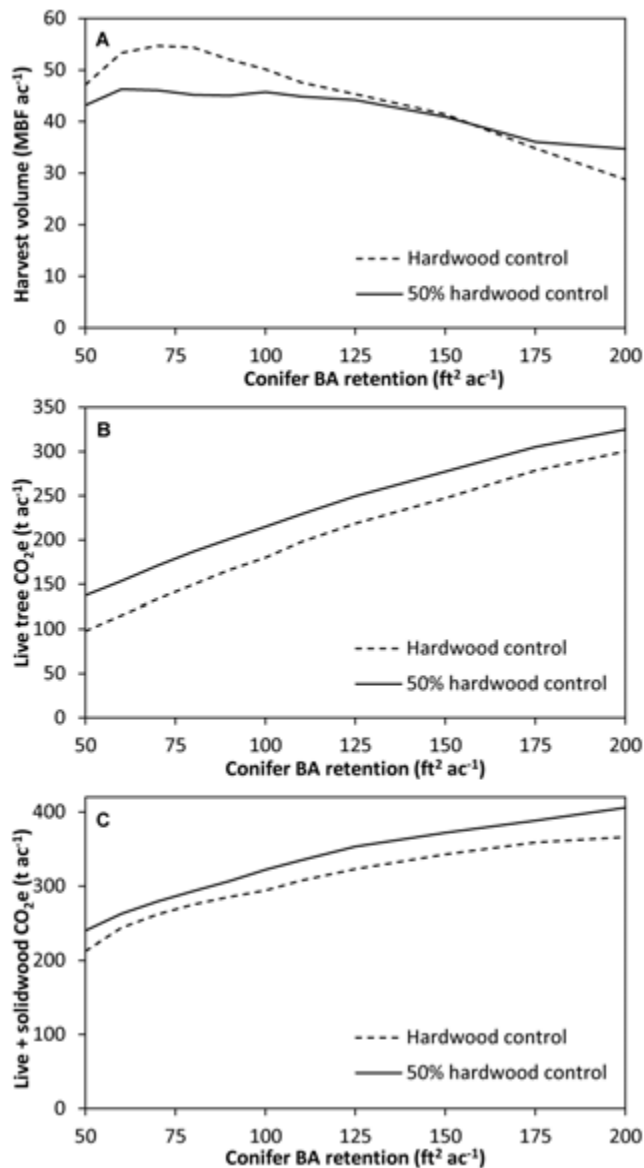


Figure 2: Total harvest volume (A) and average carbon storage in live trees (B) combined with solid-wood products (C) over 100-year modeling period for range of conifer retention levels plus cutting either 50% of hardwood BA or a more intense hardwood control prescription retaining only 5 ft² ac⁻¹ of hardwood BA at harvest in year 0, 20, 40, 60, and 80. Assumptions: no hardwood sprouting (chemical control of cull hardwood), and 30 tpa Douglas-fir natural seedling regeneration after each harvest.

umes summed over 100 years. Only controlling 50% of hardwood BA at each entry had a negative impact on the total conifer harvest when compared against the more aggressive hardwood control, but only for prescriptions

retaining up to 125 ft² ac⁻¹ of conifer BA at each entry. At higher levels of conifer retention, the total conifer harvest volume was similar under each hardwood treatment prescription (Figure 2B). The enhancement in 100-year live tree CO₂e by retaining 50% of the hardwood BA at each entry outweighed the enhanced CO₂e storage in long-lived solid-wood products associated with greater conifer harvests at the lower (5 ft² ac⁻¹) hardwood retention. The combined live-tree and solid-wood carbon storage was around 7-9% greater when 50% of hardwood BA was retained, as opposed to retaining only 5 ft² ac⁻¹ hardwood BA at each entry (Figure 2C).

3.3 Influence of hardwood control

Inexplicably, when hardwoods were cut and allowed to re-sprout from cut stumps, the total conifer harvest volume over 100 years was greater than when the hardwoods did not re-sprout (Figure 3A). Unexpectedly, carbon storage in live trees was comparable in stands with/without re-sprouting hardwoods at all levels of conifer retention (Figure 3B). As a consequence, the combined carbon storage in live trees plus long-lived solid-wood products was the same or greater when hardwoods re-sprouted after cutting compared against the hardwood control prescription when herbicide-killed hardwoods did not re-sprout. Specifically, carbon storage was 6-7% greater without the more-aggressive hardwood control at conifer retention levels >100 ft² ac⁻¹ (23 m² ha⁻¹) BA (Figure 3C).

4 DISCUSSION

In this mixed conifer-hardwood forest type, the model predicted that total harvest volume over 100 years was maximized at conifer retention levels around 60-80 ft² ac⁻¹ BA. We expect conifer regeneration to maintain vigor at these relatively low stand densities (Reineke 1933; Berrill and O'Hara 2009; Berrill et al. 2013; O'Hara 2014). Above these levels of conifer retention, a steady increase in carbon storage in live trees and long-lived solid-wood products come at the expense of harvest volume in years 0 and 20. High conifer BA retention led to greater per-acre wood volume growth, but little to no conifer harvesting occurred for 20-40 years. Conversely, lower conifer retention levels allowed for more harvesting earlier in the 100-year modeling period. Douglas-fir trees are expected to maintain vigor at low densities (Drew and Flewelling 1979; Long and Daniel 1990); however, conifer retention below 50 ft² ac⁻¹ BA had very low harvest volumes and carbon storage. Upfront payments for ecosystem services such as carbon storage in live trees and wood products might allow landowners to forego greater near-term harvest revenues (i.e., from low conifer retention prescriptions) and implement high-

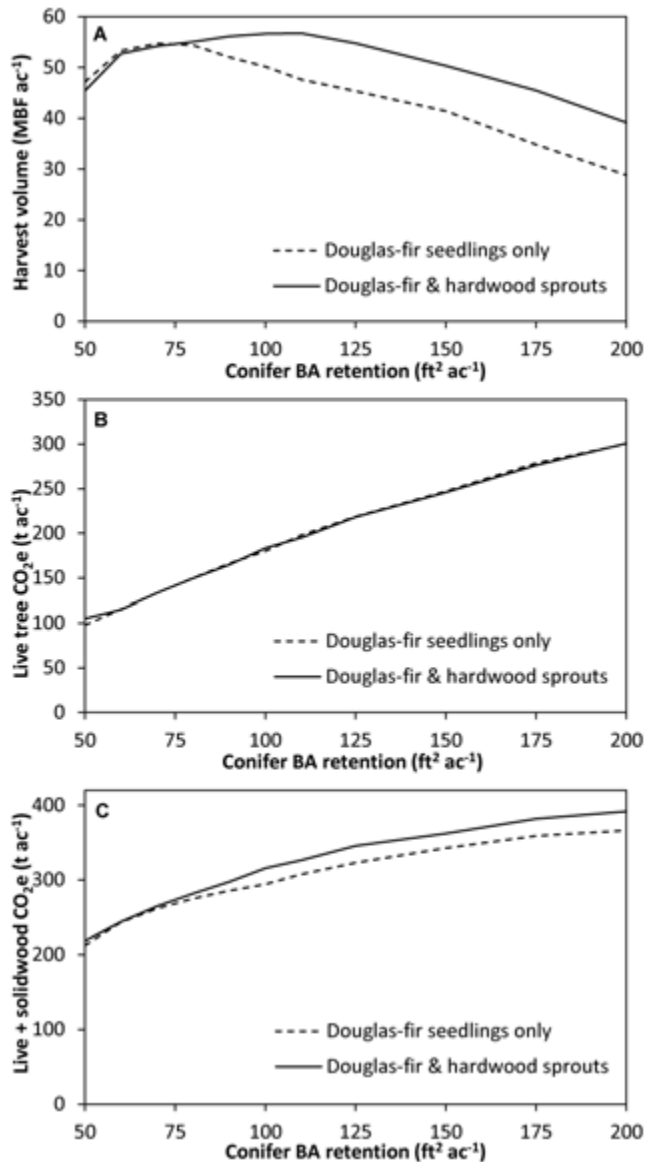


Figure 3: Total harvest volume (A) and average carbon storage in live trees (B) combined with solid-wood products (C) over 100-year modeling period for range of conifer retention levels and retaining only 5 ft² ac⁻¹ of hardwood BA at harvest in year 0, 20, 40, 60, and 80, and 30 tpa Douglas-fir natural seedling regeneration with/without hardwood sprouting (with/without chemical control of cull hardwood) after each harvest.

density prescriptions with equivalent long-term harvest yields plus greater revenues from carbon.

Thus, an illogical model prediction was identified where more conifer volume was available for harvest under prescriptions without herbicide control of hardwoods. These simulation results do not agree with

data collected in field experiments where hardwoods resprouting after cutting had a detectable negative impact on growth of conifer seedlings (Harrington et al. 1991; Berrill et al. 2018). Chemical control of hardwoods enhanced survival and development of planted Douglas-fir seedlings (Helgeson 1990). Redwood trees in multiaged stands have shown substantial positive growth responses to the control of competing hardwoods by stem injection of herbicide (Howe 2014; Berrill and Howe 2018). Young even-aged Douglas-fir responded well to herbicide release (Radosevich et al. 1976). Less is known about the response of multiaged Douglas-fir to hardwood control, such as prescriptions simulated in our study. Therefore, a priority for future research is to study the response of multiaged Douglas-fir trees and regeneration to removal of competing hardwoods.

Hardwood control practices have evolved, but the regional growth and yield model FORSEE is not designed or calibrated to predict responses to these treatments. Contemporary hardwood treatments such as frill treatment with imazapyr were not being applied in stands where data were collected for model development (Minogue 1997; DiTomaso et al. 2004). Additionally, multiaged management is being widely applied whereas the models were developed with predominantly even-aged stand data (Krumland 1982). In response to these data deficiencies, we have initiated field studies and long-term experiments at various sites to quantify treatment responses. Data from these studies will allow us to better calibrate existing models or develop new growth and yield models that account for hardwood competition and simulate a wider range of silvicultural prescriptions designed to meet timber production objectives and provision other ecosystem products and services such as carbon sequestration and storage.

Forest managers have various options for managing the tradeoff between timber and carbon. Their choices will affect the timing of treatment costs and timber revenues. One scenario involves investment in restoration treatments then waiting for future harvest revenues. Rather than harvesting a few conifers from hardwood-dominated stands to generate revenue, chemical thinning of hardwoods would enhance growth of the residual conifers at low cost (Howe 2014; Berrill and Han 2017). Then, partial harvesting at the next entry would capture the benefits of the enhanced conifer growth. Alternatively, it may be most efficient and profitable to clearcut and regenerate a conifer-dominated stand or implement group selection to regenerate patches of conifer (Berrill and Han 2017). Yet another approach would be to progressively raise the retention level at each successive harvest. For example, retaining the minimum allowable BA after the first harvest would maximize immediate timber revenues under multiaged management,

but the low-density residual stand then would store and sequester less carbon. Then, at each subsequent harvest entry, progressively higher retention would enhance carbon storage because more live trees would be retained. Higher retention would also enhance carbon sequestration and future harvest revenues because higher residual stand density leads to greater volume production (Oliver and Larson 1996; Berrill and O'Hara 2009). Even if forest owners and managers do not participate in carbon markets, our findings show how their management decisions affect carbon dynamics and how carbon sequestration and storage might be enhanced.

5 CONCLUSION

In this mixed conifer-hardwood forest, the regional model approved for use in carbon offset projects did not predict a positive response among residual conifers to hardwood control treatments. This finding was counter to our expectations and recently published studies in other forest types, suggesting that the model should be validated or refitted with repeat measures data from stands that have undergone various levels of hardwood control and partial harvesting.

ACKNOWLEDGEMENTS

We thank the Humboldt State University forestry class FOR 430/530 of fall 2017 for assistance with FORSEE modeling. Support for this study was provided by the McIntire-Stennis Cooperative Forestry Research Program

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