For. Sci. 63(1):128–135
http://dx.doi.org/10.5849/forsci.16-061

silviculture

Carbon, Harvest Yields, and Residues from Restoration in a Mixed Forest on California's Coast Range

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We simulated growth and yield over a century of restoration activities in a mixed evergreen conifer stand in northern California. Our goal was to compare ecosystem products and services, namely carbon storage, harvest yields, and residue production, among restoration-oriented silvicultural prescriptions promoting conifer dominance. We compared individual-tree selection and group selection with replanting conifers after clearcutting and "no harvest" scenarios. Ignoring risk of wildfire or forest health problems, we found that the crowded, untreated stand stored the most carbon per acre in live trees. Among the scenarios involving harvesting, high-density individual-tree selection had the greatest carbon storage because the higher density afforded high levels of production and storage of carbon in live trees. Conversion toward conifer dominance was rapid when conifers were replanted after clearcutting or low-density individual-tree selection (preferentially removing hardwood while releasing existing and planted conifers). Group selection had high harvest yields. Implementing group selection and managing the forested matrix between openings gave a steadier flow of sawlogs and residues; however, less carbon was being stored per acre in live trees growing vigorously within and between openings. Implementing an assortment of these prescriptions would provide an ongoing supply of logs and residues around which processing infrastructure and markets could develop.

Keywords: carbon sequestration, forest management, harvest residues, uneven-aged silviculture, woody biomass

Projections of forest growth and yield can be used to estimate forest residue yields and carbon sequestration and storage services (Bettinger et al. 2009). Estimates of the available supply of forest-harvesting residues, over time and space, underpin investment in infrastructure such as biomass energy plants (Hall 2002). Projections of carbon storage in live trees and long-lived wood products are needed to sell carbon offsets (Malmsheimer et al. 2011). Diversification of income from forest products and ecosystem services can buffer against downturns in log markets. Additional income streams might give landowners more flexibility to manage their forests for outcomes other than short-term yield of merchantable sawlogs. Projections of forest growth and yield under different silvicultural regimes make us aware of differences and any tradeoffs between forest products and services among forests with different structure and composition (Weiskittel et al. 2011).

The upland forests on warmer and drier parts of California's Coast Range were logged throughout the 1900s and left to regenerate naturally with hardwood and conifer. Once dominated by large conifers, these mixed evergreen conifer forests now have an overabundance of hardwoods (Supplemental Figure S1).[S] Most common are tanoak (*Notholithocarpus densiflorus* [Hook. & Arn.] Manos et al.) seedlings and stump sprouts mixed with coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco). Competition from tanoak can have a profound impact on growth of Douglas-fir (Harrington and Tappeiner 2009). Current ownership patterns and forest management practices include industrial forestry companies harvesting and planting conifers and using herbicide to control hardwoods, not-for-profit owners engaged in partial harvesting and underplanting with conifers, and many small unmanaged private holdings.

Crowded young forests on drier sites along the Coast Range are fire-prone and vulnerable to insects and disease. Tree crowns rise as competition intensifies, impacting tree vigor and presumably the ability to defend against insects and disease or respond to release (Oliver and Larson 1996). Dying trees with high crowns may not intensify fire behavior, but their numerous small crowns do contribute to high canopy bulk densities. Dead trees that fall contribute to surface fuels that drive fire behavior (Sugihara 2006). Tanoak stems are usually killed by heat from fires, but resprout from root systems that survive wildfire (Sugihara 2006). Larger conifers have thicker

Manuscript received March 22, 2016; accepted July 12, 2016; published online September 15, 2016.

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Acknowledgments: *Support from Agricultural Research Initiative (ARI) for Humboldt State University funded this research.*

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/forsci.16-061.

bark that may protect them during all but the most destructive wildfires (Agee 1996). However, crowding in unmanaged forests restricts tree size development.

Treatments that reduce stand density are expected to mitigate extreme fire behavior. However, their benefits will change over time as trees grow and become more fire resistant, harvest residues decay and alter the rate of spread of ground fire, and regeneration develops into fuel ladders that might allow fire to move from the ground into the forest canopy and be more destructive. Cutting all but the largest most vigorous tanoak (important for wildlife habitat and forage) to relieve crowding and replanting with the faster-growing merchantable conifers Douglas-fir and coast redwood (*Sequoia sempervirens* [D Don] Endl.) have the potential to enhance overall forest health and productivity (Tappeiner et al. 2007, Berrill and O'Hara 2014, 2016). Management focused on restoring conifer dominance can be considered "forest rehabilitation" defined by Lamb and Gilmour (2003, p. 14) as "re-establishing the productivity and some, but not necessarily all, of the plant and animal species originally present." Removal and utilization of forest harvest residues should make use of carbon otherwise released to the atmosphere when residues decay, while reducing surface fuel loading to mitigate the risk of wildfire that kills trees storing carbon (Jain et al. 2012). However, residues modify the forest floor environment through mulch effects that can enhance seedling development (Harrington et al. 2013), and residue removal may impact long-term productivity on some sites (Achat et al. 2015), although this is less likely on California's fertile soils (Powers et al. 2005).

Residues include materials leftover from timber harvest such as branches and culled pieces of stemwood, as well as small-diameter trees and species that are not economically feasible to harvest due to low market values. Costs of harvesting and hauling residues can be high and lack of markets causes these types of materials to be left on harvested sites instead of being used (Han et al. 2004, Kizha et al. 2015). Recent studies show that a stump-to-truck cost of residue recovery operations was around \$30/bone dry ton (BDT) not including hauling materials to a power plant (Harrill and Han 2010, Bisson et al. 2016). By adding hauling cost, the total cost of residue harvest and transportation often exceeds local biomass market values (i.e., up to \$50/BDT) in northern California. In situations where residues are not used, the current practices of residue management include "scatter on site and let decay," "pile and burn," "broadcast burn," or "mastication." It costs \$300–800/acre to manage residues after clearcut harvest in industrial timberlands (Mike Alcorn, pers. comm., Green Diamond Resource Company, Jan. 10, 2016), and residue burning can negatively impact air quality.

Reducing greenhouse gas (GHG) emissions to 1990 levels statewide by the year 2020 is the primary objective of the California Global Warming Solutions Act of 2006 (AB 32). Forest rehabilitation projects along the Coast Range of northern California should further that objective by enhancing carbon sequestration and storage in healthy, resilient, fire-resistant, productive, conifer-dominated forests. In theory, forest rehabilitation projects provide GHG emission reduction benefits via the following:

1. timber harvesting to produce long-lived solidwood products that store carbon instead of letting trees in crowded stands die and release carbon to the atmosphere via decay, and
2. restoring higher rates of forest growth and carbon sequestration by returning species composition to the more productive historical conditions under which fast-growing conifers dominated.

AB 32 requires that projects demonstrate GHG emission reductions that are real, permanent, quantifiable, verifiable, and enforceable by the state board. Installation of permanent monitoring plots allows for GHG emission reductions to be verified after postharvest plot data are collected repeatedly over time. These data can be used to validate projections of stand development and carbon sequestration from growth models. In the absence of long-term data sets, forest growth and yield models allow us to compare different forest management prescriptions in terms of harvest yields, residue production, and carbon storage over extended periods, albeit with some uncertainty (Melson et al. 2011).

The goal of this simulation study was to quantify ecosystem products and services derived from different approaches to converting unmanaged naturally regenerated forests into productive conifer-dominated forests. Our specific objectives were to examine the influence of stand density and silvicultural regeneration method on species composition, forest growth and yield, residue production, 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 replanting merchantable conifers after clearcutting or partial harvesting. We also developed "no harvest" scenarios that may reveal the benefits of 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.

Methods

Growth and Yield Modeling

To generate estimates of basal area (BA) development, harvest yields and residue production, carbon in live biomass and sawn timber, and total carbon dioxide equivalent (CO_2e) net gain, we used FORSEE (Build_26, released February 2015) to model stand growth, yield, and carbon. FORSEE is approved for growth and yield modeling in carbon offset projects by the California Air Resources Board.[1] Pure and mixed stands of species native to California's Coast Range can be modeled in a variety of even-aged and multiaged stand structures. The individual-tree 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 poorer 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 at base age 50 years) to represent the pretreatment condition (FORSEE Stand DR3D_41). Stand BA was 209 ft^2 $acre^{-1}$, comprising 1,083 trees per acre (tpa) including 75 ft^2 $acre^{-1}$ BA of conifer numbering 70 tpa (hardwood outnumbered conifer by >14:1). Average tree size (quadratic mean) was 13.8 in. dbh for conifers and 5 in. dbh for hardwoods. Stand density index (SDI) for all species combined was 454 or 76% of the maximum SDI for Douglas-fir (Reineke 1933).

We simulated eight forest management scenarios, including two without harvesting, one clearcut scenario, and five multiaged management scenarios. The multiaged treatments designed to favor conifer over hardwood were modeled through a series of different FORSEE harvest routine settings at intervals of 20 years (Supplemental Table S2). Individual-tree selection (IS) was implemented through a series of different harvests (each followed by underplanting of redwood and Douglas-fir in equal numbers) until a balanced uneven-aged condition with five age classes (cohorts) was reached. At each partial harvest, low-density IS reduced BA to 80 ft^2 $acre^{-1}$ (including at least 5 ft^2 $acre^{-1}$ hardwood) and high-density IS reduced BA to 120 ft^2 $acre^{-1}$ (including at least 10 ft^2 $acre^{-1}$ hardwood). Group selection (GS) involved creating a series of openings (up to 2.5 ac each, per California law, covering 20% of the forest area) which were modeled as miniature even-aged stands, regenerated with redwood and Douglas-fir, and thinned repeatedly every 20 years to control stand density over the 100-year modeling period. For example, immediately after partial harvesting in year 40, 20% of the forest area had new GS openings (age 0 years), 20% of the area had openings with 20-year-old regeneration, 20% of the area had openings with 40-year-old regeneration, and the remaining 40% of the area was "matrix" of forested area surrounding the GS openings. The matrix was left untreated under the GS prescription and modeled under the "let grow" (no cut) prescription. Alternatively, GS was combined with IS (GS + IS) for which the matrix received partial harvesting every 20 years and was modeled as either low-density or high-density IS with a 20-year cutting cycle to coincide with thinning operations in regenerated GS openings and new GS openings being created over 20% of the area every 20 years (gradually replacing the matrix with GS openings) (Supplemental Figure S2). The "clearcut and replant conifer" (CC) prescription involved the same series of treatments that were applied in a GS opening. Chemical control of hardwoods in the "chemical only" treatment was simulated in FORSEE by thinning to leave 5 ft^2 $acre^{-1}$ hardwood without cutting any conifer and then growing the (now conifer-dominated) residual stand for 100 years.

The following assumptions were made with respect to modeling harvesting and regeneration with FORSEE: harvest treatments were applied at the beginning of 5-year modeling time steps; sprout regeneration was set to zero to reflect planned application of herbicides to unwanted hardwood; planted redwood and Douglas-fir seedlings were introduced into model runs after each selection harvest, but were only introduced into GS openings after they were created, not after subsequent precommercial or commercial thinning operations. FORSEE harvest routine settings are provided in Supplemental Table S3. Without information on how to model enhanced growth of edge trees adjacent to GS openings or reduced growth of regeneration near edges of GS openings, we assumed that these effects offset each other in GS and GS + IS prescriptions and modeled the 2.5-acre GS openings as even-aged stands.

Carbon Calculations

Cubic stemwood volume per acre predicted using FORSEE was converted to pounds by applying a factor of 26.77 for conifer (mainly Douglas-fir) and 30.14 for hardwoods (mainly tanoak) (California Air Resources Board 2014). Pounds were converted to metric tons using a factor of 0.000453592 and CO_2e using a factor of 1.8333, ignoring possible but unknown variations in wood density and carbon fraction between prescriptions (Jones and O'Hara 2012). Mass of the stemwood component was converted to total aboveground biomass according to tree size using the stemwood biomass ratio equations of Jenkins et al. (2003) for conifer = $e[-0.3737 - 1.8055/(\text{dbh} \times 2.54)]$ and hardwood = $e(-0.3065 - 5.424/(\text{dbh} \times 2.54))$. Metric tons per acre of CO_2e stored aboveground in live trees was averaged for each 20-year period between harvest treatments (e.g., at time 0, 5, 10, 15, and 20 years) throughout the 100-year modeling period.

Regional mill efficiency data for north coastal California softwoods (×0.675) was applied to CO_2e in cubic harvested stemwood volumes (giving 67.5% wood products and 32.5% sawmill residues). The wood product volume was adjusted (×0.97) to reflect the regional recovery rate of 97% in long-lived solidwood lumber products.[2]

Biomass and Residue Production

Harvest yields predicted in units of cubic stemwood volume were converted to BDTs for hardwoods and conifers. The difference between stemwood mass and total aboveground biomass was designated harvest residue mass. Our calculations did not deduct any biomass that may have been lost to decay or other damage. Keeping residue mass identified as "conifer residues" or "hardwood residues" allowed us to sum residues for each group separately or combined in various harvesting and residue production scenarios. We calculated residue production from conventional harvest systems extracting logs and whole-tree harvesting with and without markets for conifer and hardwood logs and residues. BDTs of residues per acre were calculated for each 20-year harvest entry and summed over the 100-year modeling period.

Results

Stand BA Development

BA development differed between the eight prescriptions (Figure 1). Modeling the "let grow" (no cut) prescription using the FORSEE "default mortality" rate resulted in unrealistically high stand density (predicted to change from the initial conditions of 1,083 tpa and 209 ft^2 $acre^{-1}$ BA to 987 tpa and 541 ft^2 $acre^{-1}$ BA after 100 years). Therefore, the mortality rate was set to "maximum mortality" to better model the elevated rate of competition-induced mortality expected among hardwood and conifer in the untreated stand. This resulted in 885 tpa and 497 ft^2 $acre^{-1}$ BA (comprising 50% conifer BA) after 100 years without treatment. Chemical control of hardwoods reduced stand BA, releasing residual conifer trees in the stand that eventually attained 316 ft^2 $acre^{-1}$ BA (83% conifer BA) after 100 years without further treatment. Clearcutting and replanting conifers involved repeated thinning that reduced BA but promoted rapid tree-size development in the even-aged conifer stand.

Under multiaged management, new GS openings progressively reduced BA of the original stand. At the same time, planted conifer regeneration within these openings was thinned every 20 years and developed rapidly. Overall this led to a gradual decline in stand BA over the 100-year modeling period as residual trees were replaced periodically by young conifers. Over time, stand BA remained approximately constant under high-density and low-density IS, comprising approximately 94% conifer BA after 100 years. Combined GS + IS resulted in heavy BA reductions, but subsequent growth was rapid among residual trees within the matrix and conifers planted in GS openings and underplanted throughout the managed matrix. Between years 80 and 100, BA development was the same for all treatments involving GS because the forest area had become completely covered by GS openings regenerated with conifers.

Harvest Yields

Combined GS + IS did not rival the high initial yield of clearcutting, but provisioned the steadiest flow of logs over the 100-year

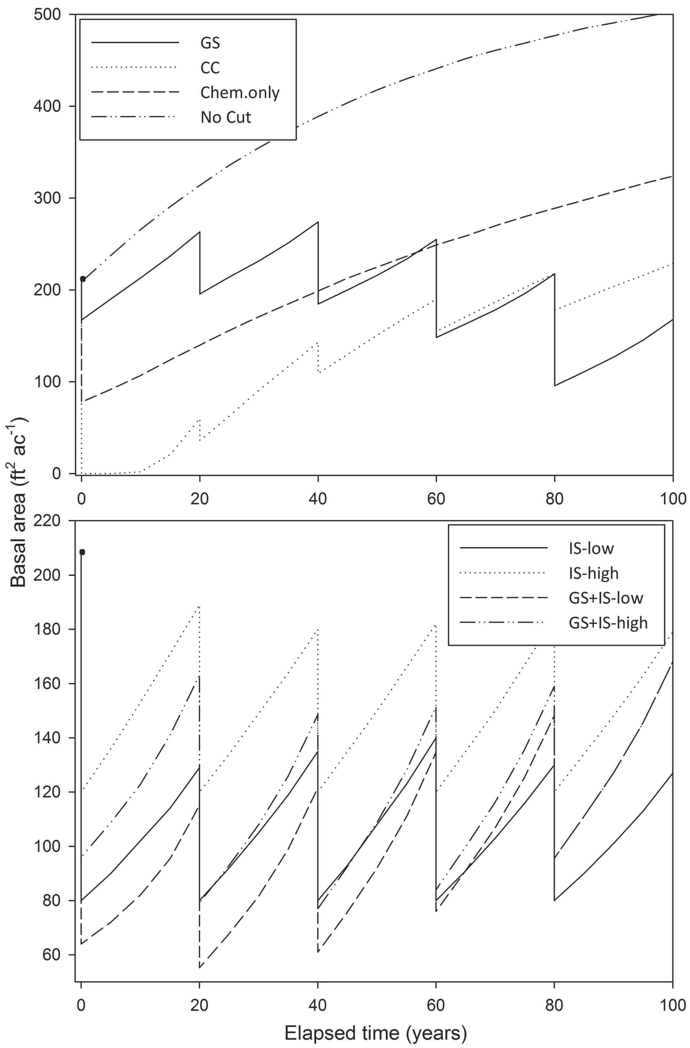

Figure 1. Stand BA development over a 100-year planning period. Top. Comparison of group selection harvest followed by repeated thinning every 20 years for 100 years (GS), clearcut and replant conifer (CC), no cut, and chemical only control of hardwood with no cutting (Chem. only). Bottom. Comparison of individual-tree selection with low-density (IS-low) and high-density (IS-high) management zones and GS combined with IS at low density (GS + IS-low) and high density (GS + IS-high) in the matrix surrounding GS openings. The black dot at year 0 denotes the pretreatment starting condition of 209 ft^2 acre^{-1}.

modeling period (Table 1). Early yields were lowest under high-density IS, where 92% of total sawlog yields came in years 40, 60, and 80 combined. High-density IS required retention of 120 ft^2 acre^{-1} BA, which only afforded a light initial cutting (year 0) to harvest hardwood and no merchantable conifer. Low-density IS allowed for some conifer harvest in conjunction with the removal of unwanted hardwoods in year 0. Conifer wood production remained low for decades after clearcutting or in GS openings until regeneration could be commercially thinned. However, high yields from periodically creating new GS openings in the dense unmanaged GS matrix led to the highest total harvest yield over the 100-year modeling period.

Carbon in Live Trees and Wood Products

Under every prescription, carbon stored aboveground in live trees had increased over the 100-year modeling period (assuming no fires or outbreaks of insects or disease). The "no cut" prescription was predicted to have the greatest 100-year average carbon stock in live trees. Among the seven prescriptions involving some form of management to reduce crowding, the "chemical only" prescription had the greatest 100-year average carbon stock in live trees. Among the six prescriptions that involved harvesting, high-density IS stored the most carbon, whereas combined GS and low-density IS stored the least carbon in live trees over the 100-year modeling period (Table 2). Harvesting and storage of carbon in conifer lumber varied over time among rehabilitation prescriptions, but overall the 100-year harvest totals were similar (Table 3).

The sum of CO_2e stored in live trees and long-lived wood products is indicative of overall carbon storage under each prescription. On a per acre basis, the no-cut prescription was predicted to have the greatest total CO_2e over the 100-year modeling period (Table 4). Combining GS and low-density IS gave the least carbon storage. Clearcutting and replanting conifer and low-density IS only gave relatively modest carbon storage. High-density IS supported the greatest total CO_2e among prescriptions involving some form of management by maintaining relatively high stand density and therefore high stand growth and yield. GS also had high carbon storage attributed to high yields of long-lived solidwood products coming from GS openings, rapid growth of young conifers planted within GS openings, and rising stand density and production in the unmanaged matrix until it had all been cut and replaced with planted conifers after 80 years. The decision to thin within GS openings every 20 years favored tree-size development over stand production and carbon stored in live trees and wood products. Forest management in the Coast Range often entails harvesting enough merchantable conifers to defray costs and making obligatory concomitant reductions in hardwood BA in accordance with California Forest Practice Rules. This can result in low stand density and, subsequently, low production. The "common practice-aboveground carbon mean" regional baseline for carbon stored in live trees for this site class III North Coast conifer forest is currently set at 205.15 metric tons acre^{-1} CO_2e.[3] Our modeling indicated that the chemical only and no-cut treatments had greater CO_2e than the common practice baseline, signifying a "net carbon gain" as a result of implementing these prescriptions. All rehabilitation prescriptions involving harvesting had lower CO_2e than the common practice baseline (Table 4).

Biomass and Residue Production

In northern California, the conventional approach to harvesting on the steep slopes and variable terrain characteristic of these forests involves a mixture of cable and ground-based logging to bring logs to small landings spaced along narrow forest roads. Hardwood logs are sometimes extracted and piled on the landing for burning or use as firewood or biomass energy. The focus of harvesting is on the extraction of merchantable conifer logs. Under this system, conifer and hardwood residues such as branches and tops remain scattered across the site or may be piled. When we simulated applying this harvest system at 20-year intervals, GS gave the greatest total yield of conifer log biomass. Similar yield from GS combined with high-density IS was more evenly distributed among harvest events (Figure 2A). The supply of conifer log biomass from an acre managed under each prescription was greatest initially after clearcutting and zero under high-density IS (only hardwoods were cut in the first entry). The supply of conifer log biomass increased progressively at each harvest entry under most prescriptions and remained elevated after

Table 1. Conifer board foot volume yields for harvested conifer (excludes cut hardwood) under each rehabilitation prescription over a 100-year modeling period.

Harvest year	IS-low	IS-high	GS	GS + IS-low	GS + IS-high	CC	Chem. only	No Cut
	(board ft acre^{-1})							
0	1,202	0	2,086	3,047	2,086	10,429	-	-
20	5,789	3,902	4,980	7,857	7,419	0	-	-
40	15,613	15,432	9,481	13,177	14,752	3,333	-	-
60	11,754	13,379	14,850	10,197	12,839	5,946	-	-
80	12,199	14,480	21,021	10,122	13,110	9,067	-	-
Total	46,557	47,193	52,419	44,401	50,205	28,775	0	0

Prescriptions: IS-low, individual-tree selection with low-density management zone; IS-high, IS with high-density management zone; GS, group selection; GS + IS, combination of treatments; CC, clearcut and replant conifer and then thin every 20 years; Chem. only, chemical control of hardwood without harvesting; No cut, no treatment (i.e., "let grow").

Table 2. Total live aboveground CO_2e averaged over 20-year periods and a 100-year average under each rehabilitation prescription.

Modeling period	IS-low	IS-high	GS	GS + IS-low	GS + IS-high	CC	Chem. only	No cut
	(metric tons acre^{-1})							
0–20 yr	113.3	146.5	126.2	90.8	117.3	0.8	119.6	157.6
20–40 yr	139.3	197.8	183.2	95.5	130.6	58.7	221.8	285.5
40–60 yr	137.1	206.6	207.1	97.8	125.6	155.4	345.3	410.4
60–80 yr	142.1	214.6	197.5	120.9	135.4	247.6	466.1	525.1
80–100 yr	145.7	219.8	156.0	156.0	156.0	317.6	574.7	624.2
100-year Average	135.5	197.1	174.0	112.2	133.0	156.0	345.4	400.4

Note: The estimates do not include harvested wood. Prescriptions: IS-low, individual-tree selection with low-density management zone; IS-high, IS with high-density management zone; GS, group selection; GS + IS, combination of treatments; CC, clearcut and replant conifer and then thin every 20 years; Chem. only, chemical control of hardwood without harvesting; No cut, no treatment (i.e., "let grow").

Table 3. CO_2e in harvested conifer converted to solidwood lumber products under each rehabilitation prescription over a 100-year modeling period.

Harvest year	IS-low	IS-high	GS	GS + IS-low	GS + IS-high	CC	Chem. Only	No Cut
	(metric tons acre^{-1})							
0	4.1	0.0	6.3	9.5	6.3	31.4	-	-
20	15.0	11.0	12.9	20.2	19.8	0.0	-	-
40	36.6	36.5	23.3	31.9	35.7	11.3	-	-
60	28.0	29.9	34.6	25.4	30.7	16.3	-	-
80	29.2	33.3	47.0	24.9	31.7	22.4	-	-
Total	112.8	110.7	124.1	111.9	124.2	81.4	0	0

Note: solidwood lumber does not include plywood and paper products. Prescriptions: IS-low, individual-tree selection with low-density management zone; IS-high, IS with high-density management zone; GS, group selection; GS + IS, combination of treatments; CC, clearcut and replant conifer and then thin every 20 years; Chem. only, chemical control of hardwood without harvesting; No cut, no treatment (i.e., "let grow").

Table 4. 100-year total CO_2e (live trees + conifer lumber) and net gain calculated as the difference between total CO_2e in live trees and common practice baseline of 205.15 metric tons acre^{-1} under each rehabilitation prescription over a 100-year modeling period.

	IS-low	IS-high	GS	GS + IS-low	GS + IS-high	CC	Chem. only	No cut
Total CO_2e (tons acre^{-1})	248.3	307.8	298.1	224.1	257.2	237.4	345.5	400.6
Net gain CO_2e (tons acre^{-1})	−69.7	−8.1	−31.1	−93.0	−72.2	−49.1	140.3	195.4

Prescriptions: IS-low, individual-tree selection with low-density management zone; IS-high, IS with high-density management zone; GS, group selection; GS + IS, combination of treatments; CC, clearcut and replant conifer and then thin every 20 years; Chem. only, chemical control of hardwood without harvesting; No cut, no treatment (i.e., "let grow").

80 years once regenerated GS openings completely replaced the original forest. Because harvest residues remained in the forest, and hardwood logs may or may not have been used; the only residues guaranteed to be coming from this system were conifer sawmill residues (Figure 2B). The multiaged prescriptions generated more residues in later years, whereas the even-aged prescription generated the most conifer mill residues in association with clearcutting in year 0. If markets were developed for hardwood logs, the total log supply (conifer + hardwood logs) would be greatest under GS but steadiest under low-density IS or GS + IS (Figure 2C), whereas GS gave the steadiest supply of hardwood log biomass (Figure 2D).

Alternatively, if we applied whole-tree harvesting, slash comprising branches and tops of the cut trees would accumulate at the landing and could be used or burned. We simulated this option, assuming that conifer logs were dispatched to sawmills, which would leave conifer slash and hardwood logs and slash available for utilization as harvest residues (Figure 2E). Under this scenario, low-density IS and GS + IS generated a steady supply of harvest residues, whereas production of residues from GS steadily increased and totaled the most residues produced over a 100-year modeling period. If conifer slash did not have a market, an operator could still perform whole-tree harvesting but only dispatch hardwood logs and slash to

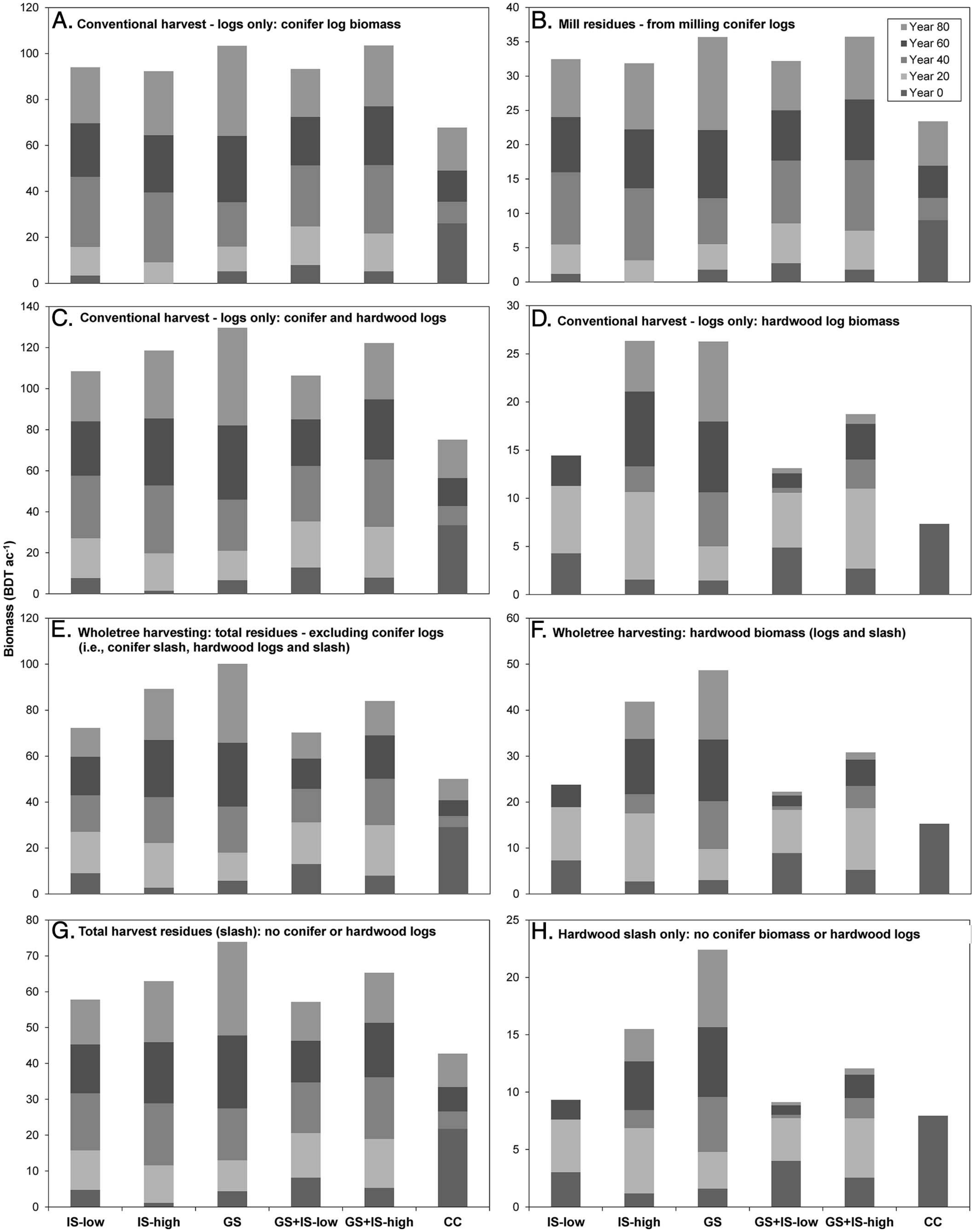

Figure 2. Biomass in BDTs for different combinations of harvested products and residues over a 100-year simulation period under rehabilitation prescriptions designed to restore conifer dominance with 20-year cutting cycles in mixed evergreen conifer stands on relatively poor sites in the California Coast Range (Douglas-fir site index of 114 ft at base age 50 years). Prescriptions: IS-low, individual-tree selection with low-density management zone; IS-high, IS with high-density management zone; GS, group selection; GS + IS, combination of treatments; CC, clearcut and replant conifer and then thin every 20 years.

market (Figure 2F). Supply of hardwood logs and slash was greatest with GS over the first 100 years, but after this time conversion to conifer dominance would be complete and hardwood yields would be negligible. Conversion to conifer dominance was immediate after clearcutting and replanting with conifer. The conversion proceeded quickly with GS + IS or low-density IS and slowly with GS or high-density IS. If new markets developed for hardwood logs (e.g., sawtimber or veneer), then whole-tree harvesting would have at least three product lines: conifer logs (Figure 2A), hardwood logs (Figure 2D), and residues comprising either conifer-hardwood slash (Figure 2G) or hardwood slash alone (Figure 2H) if no market existed for conifer slash. Biomass of conifer slash comprised 51–70% of total whole-tree harvest residues, with its share and amount of the total residue stream increasing as hardwoods were progressively replaced by conifers under the various rehabilitation treatments.

Discussion

The wide-ranging rehabilitation prescriptions were designed to represent realistic options for improvement of crowded, hardwood-dominated Coast Range forests. Harvesting and replanting conifers is compatible with timber production objectives and promoting development of old-growth forest structure by regenerating new cohorts of conifers and enhancing forest productivity, health, and resilience (Berrill et al. 2013). Retention levels (low and high density) were calculated using the upper limit of stand density for Douglas-fir (Reineke 1933) and the principles of stand density management described by Long (1985) and later applied to uneven-aged stands by Long and Daniel (1990) and Shaw (2000). The decision to select upper limits of 30 and 50% relative density for low- and high-density management zones was supported by simulation studies (Berrill and O'Hara 2009), indicating that these represented lower and higher levels of stand density that should allow for adequate site occupancy, cubic (carbon) and board foot volume production, and regeneration vigor. High-density IS surpassed low-density IS in terms of carbon stored in live trees (Table 2), but to a lesser extent in total CO_2e (Table 4) because total conifer harvest yields (Table 1) and carbon stored in wood (Table 3) were roughly equivalent. 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 clearcutting or low-density IS or GS + IS) and implement high-density prescriptions with equivalent long-term harvest yields plus greater revenues from carbon. Implementing an assortment of different rehabilitation treatments across the landscape would not generate as much carbon revenue as implementing only high-density prescriptions but would generate a steadier, sustained yield of sawlogs and residues to underpin investment in processing infrastructure. Failure among most of our prescriptions to meet or exceed the common practice baseline of 205.15 metric tons acre^{-1} CO_2e suggested that this value, which also applies to highly productive coast redwood forests, may not be appropriate for this site class and forest type.

Our projections assumed no wildfire or other catastrophic disturbances. This may not be realistic, especially in crowded stands. Harvesting reduces crowding, and harvest residues and unwanted nonmerchantable trees could be extracted using whole-tree harvesting or treated using various fuels treatments to reduce risk or the impact of wildfire (Stephens et al. 2009, Jain et al. 2012). Treatment or extraction of harvest residues can be integrated into harvesting systems (Vitorelo et al. 2011, Harrill and Han 2012) and offers positive benefits without notable impacts to other ecosystem values (Stephens et al. 2012). In the absence of harvesting, we calculated that SDI attained 600, the biological maximum for Douglas-fir (Reineke 1933), after only 20 years of the 100-year modeling period. This was after modeling growth using the maximum mortality rate adjustment in FORSEE, which does not account for sudden oak death (*Phytophthora ramorum*) that is killing tanoak throughout the region (Rizzo and Garbelotto 2003, Ramage et al. 2012). Higher densities have been measured in old-growth mixed evergreen conifer stands with components of coast redwood, Douglas-fir, and tanoak for which BA ranged from 525 to 700 ft^2/acre and SDI ranged from 590 to 770 (Berrill et al. 2013), but we are not aware of such high densities measured in second-growth Douglas-fir/tanoak stands. We therefore expect insect damage and disease to result in accelerated tree mortality and associated increases in surface fuel loads in the absence of harvesting (Oliver and Larson 1996). Reducing stand density through chemical control of hardwoods does not constitute harvesting and offered favorable carbon net gain (Table 4) at low cost. Frill and spot spray treatments are inexpensive (Howe 2012) and alone can be implemented without preparing a (costly) timber harvest plan in accordance with California Forest Practice Rules. The dead-standing hardwoods break down gradually and are replaced by conifers with thicker bark that is more resistant to fire (Valachovic et al. 2011, Ramage et al. 2012).

We recommend implementing all of the rehabilitation treatments side-by-side to create opportunities for monitoring of growth, yield, and carbon. These data could be used to validate forest growth and yield models, or, if needed, reparameterize these models or develop the next generation of growth models that better predict carbon sequestration in carbon offset projects prescribing uneven-aged management for forest restoration. We recommend validation of regeneration growth models across gradients of understory light and belowground competition known to affect conifer growth rates (Devine and Harrington 2008, O'Hara and Berrill 2010) because regeneration is an important component of sustained yield in multiaged stands (O'Hara 2014) and structural diversity in restored mixed evergreen conifer stands (Berrill et al. 2013). We also recommend analysis of risk of carbon loss from wildfire under each rehabilitation prescription using real fuels data to model fire behavior (Reinhardt and Dickinson 2010). This will help forest owners and managers understand the tradeoffs between product yields, ecosystem services, and wildfire risks and prescribe the appropriate combination of treatments for their ownership and management objectives.

Endnotes

1. For more information, see www.arb.ca.gov.
2. For more information, see Regional Mill Efficiency Data.xls and Harvested Wood Products worksheet in Area Assessment Data File.xls available online at www.arb.ca.gov/cc/capandtrade/protocols/usforest/usforestprojects_2015.htm.
3. For more information, see the Area Assessment Data File.xls available online at www.arb.ca.gov.

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