CARBON BALANCE ON FEDERAL FOREST LANDS OF WESTERN OREGON AND WASHINGTON:

THE IMPACT OF THE NORTHWEST FOREST PLAN

Olga N. Krankina[a], Mark E. Harmon[a], Frank Schnekenburger[a], Carlos A. Sierra[ab]

[a]Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA

[b] *Present address*: Max-Planck-Insititute for Biogeochemistry, Hans-Knöll-Straße 10, 07745, Jena, Germany, csierra@bgc-jena.mpg.de

Corresponding author:
Olga N. Krankina
Department of Forest Ecosystems and Society
Oregon State University
Corvallis, OR 97331
USA

Phone: 1-541-737-1780
E-mail: krankinao@fsl.orst.edu

ABSTRACT

The management of federal forest lands in the Pacific Northwest (PNW) region changed in early 1990s when the Northwest Forest Plan (NWFP) was adopted with the primary goal to protect old-growth forest and associated species. A major decline in timber harvest followed, extending an earlier downward trend. The historic and projected future change in carbon (C) stores and balance on federally managed forest lands in Western Oregon (OR) and Western Washington (WA) was examined using the LANDCARB 3.0 simulation model. The projections include C stores on-site, in harvested wood products and disposal and reflect a set of contrasting visions of future forest management in the region formulated as 5 alternative management scenarios that extend to year 2100. A significant and long-lasting net increase in total C stores on federal forest lands relative to early 1990s level was projected for both OR and WA under all examined management scenarios except the *Industry Scenario* which envisioned a return to historic high levels of timber harvest. In comparison with the *Industry Scenario*, the low levels of timber harvest under the NWFP between 1993 and 2010 were estimated to increase total C stores by 86.0 TgC (5.1 TgC yr^{-1} or 2.16 MgC ha^{-1} yr^{-1}) in OR; in WA the respective values were 45.2 TgC (2.66 TgC yr^{-1} or 1.33 $MgCha^{-1}$ yr^{-1}). The projected annual rate of C accumulation, reached a maximum between 2005 and 2020 approaching 4 TgC yr^{-1} in OR and 2.3 TgC yr^{-1} in WA, then gradually declined towards the end of projection period in 2100. Although not the original intent, the NWFP has led to a considerable increase in C stores on federal forest lands within the first decade of plan implementation and this trend can be expected to continue for several decades into the future if the limits on timber harvest set under the NWFP are maintained. The primary goal of the NWFP to protect and restore old-growth forest may take several decades to achieve in WA whereas in OR the area protected from clearcut harvest may be insufficient to meet this goal before the end of projection period in 2100.

Keywords

Forest management; landscape carbon stores; timber harvest; old-growth conservation; Pacific Northwest

Highlights

- Model projected forest carbon stores in Oregon and Washington to year 2100
- Carbon stores and patterns of change over time differed under alternative management scenarios
- Continuation of the Northwest Forest Plan was projected to increase carbon stores
- Return to high levels of timber harvest was projected to reduce carbon stores
- Current management allows conservation of old-growth forest in Washington but not in Oregon

1. Introduction

Forests are a critical part of the global biological carbon (C) cycle and their management may contribute to stabilizing the concentration of the greenhouse gas C dioxide in the atmosphere (Pacala and Sokolow 2004). The potential of forest ecosystems to store C is well established (e.g., Post et al. 1990, Nabuurs et al. 2007, Keith et al. 2009), but the degree to which this potential is being met under different management systems is uncertain. The conversion of older forests to younger forests has generally been shown to release C to the atmosphere (Cooper 1983, Harmon et al. 1990, Dewar 1991, Harmon and Marks 2002, Trofymow et al. 2008) and management decisions regarding remaining older forest stands is an important factor in determining how the C balance of forest landscapes changes over time. This is especially important in the Pacific Northwest (PNW) where forests have some of the highest biological potential to store C (Harmon et al. 1990, Smithwick et al. 2002, Birdsey et al. 2007). The PNW is also the region where substantial remnants of productive, high-biomass old-growth forests have survived (DellaSala 2011) whereas in other temperate forest regions they have been eliminated for centuries. Carbon inventories in the productive high-biomass old-growth forests of the PNW provide a robust measure of the upper limit of C storage (Smithwick et al. 2002) which is rarely available to assess the full potential of C sequestration associated with restoring late-successional forests.

The PNW region has recently experienced major changes in forest management. The adoption of the Northwest Forest Plan (NWFP) in 1994 resulted in a significant decline in timber harvest on federal forest lands extending an earlier downward trend (e.g., Alig et al. 2006). For example, in Oregon (OR) during the peak harvests in the 1970s and 1980s, over 5 billion board feet (BBF, Scribner scale) [1] per year were removed from federal forest lands; in the early 1990s timber removals were about half that amount and in early 2000s the harvest fell below 0.5 BBF (Warren 2008). This recent period of low timber harvests can be expected to cause significant changes in forest C stores at present and for many decades into the future if the provisions of the NWFP are maintained.

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[1] Approximately 24 million m^3. The conversion factor from thousand board feet (MBF, Scribner long-log scale) to cubic meters increased from approximately 4 to 4.5 in the 1970s to greater than 7 by 1998 (Spelter 2002). In early 2000s 0.5 BBF was approximately 3.6 million m^3.

The NWFP assumed that forests in 0.7 percent of the Plan area would be lost to stand-replacing wildfire per decade, and that 1 percent of the entire Plan area (or 3 percent of total late-successional forest area) would be harvested per decade (i.e., a 0.17% yr^{-1} combined annual rate of disturbance). Monitoring results, albeit short-term, suggest that during the first 10 years of the Plan estimated gains of older forest far outpaced losses, resulting in a net increase of between 1.25 and 1.5 million acres (500-600 thousand ha) of older forest on federally managed land. This rate of gain was about twice the first decadal gain expected under the Plan (Mouer et al. 2005).

Several regional studies used different methods to examine recent changes in the C balance of PNW forests. Following peak timber harvest of the 1980s, forests of the PNW were losing C (Cohen et al. 1996, Song and Woodcock 2003) with losses of coarse woody debris representing a significant permanent loss not compensated by regrowth (Harmon et al. 1990). A net uptake of 13.8 TgC yr^{-1} (1.68 MgC ha^{-1} yr^{-1}) was estimated using Biome-BGC model for forests of western OR in 1995-2000; after accounting for harvest removals and fire emissions the regional net biome production (NBP) was reported at 8.2 TgC yr^{-1} (1.00 MgC ha^{-1} yr^{-1}, Law et al. 2004). An expanded state-wide assessment by Turner et al. (2007) estimated NBP in 1996-2000 at 6.1±10.2 TgC $yr^{-1}$with climate fluctuations responsible for significant interannual variation. Most of the reported C sink was associated with public forest lands in western OR. Net C uptake in OR forests in 2000-2005 estimated from Biome-BGC simulations (1.10 MgC ha^{-1} yr^{-1}) was consistent with the estimate derived from forest inventory data (1.33±0.29 MgC ha^{-1} yr^{-1}; Turner et al. 2011). While there is a general consensus that the forests managed under the NWFP have been net sinks of C in recent years and that declining timber harvests contributed to this sink, there is little agreement on expected future changes in the C balance of these forests and the role of management decisions in historic and future C dynamics. Furthermore, it is unclear how long into the future the provisions of the NWFP will be maintained as alternative approaches to the management of federal forest lands are being proposed, including a return to higher timber harvest levels (e.g., BLM 2008).

Climate change is generally expected to reduce C uptake and increase losses to the atmosphere in PNW forests through decline in forest productivity and increased intensity and frequency of wildfires (e.g., Law et al. 2004, Lenihan et al. 2008, Crookston et al. 2010). Other studies project regional C sinks for decades into the future even with timber harvests exceeding the planned NWFP levels (Smith and Heath 2004, Alig et al. 2006, Im et al. 2010). The contradictory conclusions regarding the impact of management decisions on C balance of PNW forests (e.g., Mitchell et al. 2012, Trofymow et al. 2008, Perez-Garcia et al. 2005, Harmon and Marks 2002) have contributed to confusion among stakeholders and decision-makers and stifled the development of effective climate change mitigation measures in the forest sector (Maness 2009).

The main objective of this study was to analyze the effect on forest sector C stores of varying levels of timber harvest in federally managed forest lands within the NWFP area of OR and Washington (WA). The LANDCARB Model (Mitchell et al. 2012) was used to simulate historic change in C stores on federal forest lands since the onset of wide-spread clear-cut logging in the 1950s up to the present time and to project future change for a set of forest management scenarios representing a broad range of alternatives that are under consideration. The analysis of results focused on assessment of change in forest sector C balance as a result of the NWFP and alternative management scenarios.

2. Methods

2.1 Study Area

The study area includes federally managed lands in the NWFP area of western OR (Coast Range, Willamette Valley, and Western Cascades) and western WA (Olympic Peninsula, Western Lowlands and Western Cascades; Fig. 1) where federal forest lands represent 39% and 33% of the total forest area, respectively (Mouer et al. 2005). The total study area is 4.3 million ha or 44% of the entire land area covered by the Plan (9.9 million ha total in OR, WA and Northern California). According to Mouer et al. (2005), at the start of the Plan older forest occupied between 30 and 34 percent (depending on the definition) of forest-capable public lands managed by the Forest Service, Bureau of Land Management, and National Park Service that were in the range of the northern spotted owl. Forests meeting the most strict definition of old-growth -- “Large, multistoried older forest” -- occupied about 12 percent of forest-capable public land. Conservation of these older forests was among the primary goals of the NWFP.

The NWFP record of decision divided federal land into seven land-use allocations; Mouer et al. (2005) combined or further split some allocations. Specifically, three categories of late-successional reserves were grouped together; lands with overlapping late-successional reserve and adaptive management area designations were treated as late-successional reserves (LSR). Administratively withdrawn and congressionally reserved lands were grouped together (AW/CR). Matrix and adaptive management areas were the land allocations where scheduled timber harvest activities may take place; these were grouped together as well as riparian reserves, which were never mapped separately from Matrix lands at the scale of the entire Northwest Forest Plan. We used these generalized land-use categories and associated area estimates for our study area in western OR and WA (Table 1).

The distribution of stands by age groups within each state and land allocation in the early 1990s (Table 1) was approximated by the proportion of different stand categories reported in Mouer et al. (2005). This report combined “Potentially forested but presently nonstocked” (PF) and “Seedling and sapling” (SS) categories into “very young” forest category (<10 inch diameter at breast height (DBH) and <20 years old); the small-sized trees (10-20 inch DBH) were labeled “young” and assigned stand age 21-60 years old; the old-growth area estimate was based on zone-indexed definition (and assigned age >150 years old) and the balance of area was presumed to be in the mature category (61-150 years old). Note that the range of stand ages included in each of these four age groups varies from about 20 years in the “Very Young” group to >300 years in the “Old-Growth” age group.

2.2 LANDCARB Model

The simulation model used for this analysis was LANDCARB 3.0, which builds on earlier modeling work (e.g., Harmon and Marks 2002) and simulates the accumulation and loss of C over time in a landscape where forest stands are represented by a set of grid cells (Mitchell et al. 2012, http://landcarb.forestry.oregonstate.edu/tutorial-modules.aspx, last visited March 24, 2012). Model simulations were run for a grid of 20 by 20 cells (400 cells total), with a cell size of 100 x 100 meters (1 hectare). In this analysis we assumed that all forested cells were initiated by either a stand-replacing wildfire or a clearcut harvest. In each year of the simulation, disturbance was assigned to a sub-set of cells and for all other cells the successional change of C stores was projected. The count of age of tree stands (cells) begins from zero in the year of disturbance and continues until the cell is disturbed again. The proportion of cells thus assigned to different stand ages approximates the age-class structure of a forest landscape. The number of grid cells in model runs was selected to be sufficient to prevent the output fluctuations from randomly prescribed natural disturbance events (fire) from obscuring the trends in C stock change over time without excessive computation time to run the model.

The proportion of landscape disturbed annually by wildfire and clearcut harvest was defined based on fire return interval and harvest rotation, respectively. The proportion of stands (cells) disturbed annually by fire is the inverse of fire return interval: e.g., 200-year fire return interval means that on average 1/200 or 0.5% of the total forest area or an average of 2 random grid cells out of 400 is disturbed per year in LANDCARB simulations. The proportion of the landscape affected annually by timber harvest relates to the harvest rotation length in a similar fashion. To approximate the variability of the area disturbed annually we modeled the probability of disturbance using the Poisson distribution. This probability distribution is used when the process being represented is discrete in time and/or space. The mean and variance of this distribution are represented by the parameter λ, which is the average number of occurrences of a certain event per unit of time. Since we are assuming that in model simulations cells would be disturbed each year based on rotation length and fire return interval, $\lambda = (1/\text{rotation length})$ or $\lambda = (1/\text{fire return interval})$, for timber harvest and fire, respectively. The model was run for 1200 years, but only the last 250-year period between 1850 and 2100 was used in the analysis and reported.

Each stand grid cell contained four layers of vegetation (upper trees, lower trees, shrubs, and herbs), each having up to seven live biomass components (C pools), eight dead pools, three stable (soil) pools representing highly decomposed material, and two pools representing charcoal. The live parts included: 1) foliage, 2) fine roots, 3) branches, 4) sapwood, 5) heartwood, 6) coarse roots, and 7) heart-rot. Each of the live parts of each layer contributed material to a corresponding dead pool. Thus foliage added material to the dead foliage, etc. All of the dead pools added material to one of three stable pools (stable foliage, stable wood, and stable soil) and fires created surface charcoal from live parts or dead pools. Sub-surface charcoal was formed from surface charcoal incorporated into the mineral soil and became protected from future fires, whereas surface charcoal was lost during subsequent fires.

The part of the LANDCARB model tracking forest products is patterned after the FORPROD model (Harmon et al. 1996). Harvested wood is processed into products that are either in-use or disposed. C stores in wood products and disposal vary according to their inputs and losses on an annual basis. In a manufacturing step, harvested wood C produces inputs for the different product C stores such as long-term structures (life-span >30 years), short-term structures (life-span <30 years), paper, and mulch. Once the new product inputs as well as losses due to combustion, decomposition, and disposal have been computed, product stores are updated each year. Disposed products can be either sent to open dumps (high combustion and decomposition rates), landfills (no combustion and very low decomposition rates), incinerated (instantaneous loss) or recycled into the original product. Stores in disposal are also updated annually after inputs and losses from decomposition and combustion are computed. The parameters used in manufacturing, product use, and disposal can vary over time to reflect changes in efficiency, uses, and disposal practices. These and other LANDCARB 3.0 model parameters are in Appendix; module structure and calculation procedures are at http://landcarb.forestry.oregonstate.edu/tutorial-modules.aspx last visited March 24, 2012.

The model outputs used in this analysis included landscape-level average C stores (total and by component: live biomass, dead, stable, products, and disposal) in each simulation year, annual net change in C stores (C balance; positive for net increases, negative for net losses), and the proportion of cells in different age groups. Five repeated runs of each management treatment were performed to allow for calculation of model output averages and standard errors.

2.3 Model Calibration

The LANDCARB model was parameterized to represent the successional change in C stores for the environmental conditions representative of western OR and WA. The model used constant monthly climate inputs that represent historic averages for selected counties in OR and WA (separately; Fig. 1). To approximate average forest growth patterns we calibrated the model projections of live tree biomass over stand age to be consistent with the average values of forest biomass by stand age derived from USDA Forest Inventory and Analysis plots (FIA data). We generated the reference data set using the Carbon Online Estimator (COLE, Van Deusen and Heath 2010, http://www.ncasi2.org/COLE/index.html) for a set of counties within the NWFP area of western OR (current as of August 28, 2009) and western WA (current as of October 23, 2009; Fig. 1).

We used COLE results for the Douglas-fir (*Pseudotsuga menziesii*) forest type which is dominant in our study region and is better represented in FIA dataset than other forest types. Within the study area this type is dominated by Douglas-fir and western hemlock (*Tsuga heterophylla*) and these two species were included in LANDCARB simulations (Appendix Table 1). Other tree species were not simulated as they account for <3% of total live tree C in Douglas-fir forest type within the study area (http://www.ncasi2.org/COLE/index.html; last visited February 29, 2012). The COLE report provided estimates for a full set of forest C pools but we used only live tree C because it is expected to be more robust than other reported estimates. The calibration of LANDCARB focused on younger age classes (<100 years old) because older forests are poorly represented in the FIA dataset with too few stands to provide robust averages. The calibration resulted in a very close alignment of live tree biomass predictions by LANDCARB and the averages of FIA plot measurements in both states (Fig. 2).

2.4 Simulation of initial conditions circa 1993

The regional fire history was represented in two different intervals:

1) prior to year 1910 a natural wildfire regime was simulated with a return interval of 200 years,

2) to represent the effects of fire suppression from 1910 onward the wildfire return interval was doubled on 50% of the cells.

This historic fire regime was simulated by LANDCARB for all three land-use allocations under the NWFP (AW/CR, LSR, and Matrix); in addition, historic timber harvest was simulated for each land-use allocation separately. The simulated distribution of cells by age classes in 1993 was compared to observed area distributions in the early 1990s (Table 1) and adjustments were made to historic logging assumptions (described below) to approximate the observations more closely.

For AW/CR lands no logging was assumed initially but simulations of the historic fire regime alone resulted in a low proportion of cells in younger age classes in 1993 as compared to observations: 19.0% of the cells were projected to be younger than 60 years by LANDCARB, while the observed proportion of stands in this age group on AW/CR lands was 55.1% in OR and 47.9% in WA (combined "very young" and "young" from Table 1). With harvests placed in 40% of grid cells in OR and 31% in WA between 1934 and 1993, the simulated proportion of younger forests was brought closer to that observed in AW/CR lands: 55.3% in OR and 47.9% in WA.

For LSR and Matrix lands the logging history was represented in 3 different periods:

1) from 1950 to 1960 logging was simulated assuming an average harvest rotation of 120 years and timber removal of 85% of stem wood to account for the fact that during this period harvests were limited by road access and utilization standards of harvest were generally low;
2) an intensification of logging was modeled from 1960 to 1965 using a 60-year rotation and timber removal of 90% of stem wood;
3) from 1966 to 1993 rotation ages varied from 50 to 100 years to approximate the reported pattern of change in harvest on federal lands (Warren 2008) and the observed stand distribution by age groups in early 1990s (Table 1). Timber removal was assumed to be 90% of stem wood.

The final simulated proportions of land area in various age groups in 1993 matched closely the observed values across all three land-use allocations in the two states (Table 1) with deviations < 0.6% in all cases.

2.3 Post-1993 Scenarios

Five post-1993 management scenarios were developed to represent contrasting visions of future forest management in the region in a generalized form, similar to the story-line scenarios used by the Intergovernmental Panel on Climate Change to project future fossil fuel emissions (IPCC 2000). These scenarios reflected a broad spectrum of management alternatives proposed for the federal lands by different interest groups, ranging from maximizing timber harvest with clearcutting to eliminating clearcutting completely and restricting timber harvest to thinning of young stands. Each scenario included a set of simple treatments for the three land-use allocations on federally managed lands in the NWFP area (Table 2). Scenarios 1-4 assumed that the fire suppression regime described above was extended to 2100 on all federal forest lands and Scenario 5 assumed no fire suppression so that the pre-1910 fire regime was restored (Table 2). In all scenarios no timber harvest was projected for AW/CR lands; for LSR and Matrix lands harvest was projected as follows:

(1)Industrial Harvest Scenario (Industry)[2]

Logging was modeled assuming a harvest rotation length of 60 years until 2100 on both LSR and Matrix lands.

(2)NWFP-planned Scenario (NWFP-p)

Logging on Matrix lands was modeled assuming a 120-year harvest rotation length until 2100, in line with the expected level of timber harvest under the NWFP (Mouer et al. 2005). The LSR lands had no timber harvest.

(3)NWFP-implemented Scenario (NWFP-i)

Logging was modeled assuming a 200-year rotation length until 2100 on Matrix lands in line with the harvest level from 1994-2004 which was below that initially planned under the NWFP (Warren et al. 2008). The LSR lands had no harvest.

(4) Conservation with Suppression of Fire Scenario (Cons – fire)

Logging was modeled in the Matrix lands assuming 50% of the stands were thinned at ages 20 and 40 years old. At each thinning 40% of the stem volume was cut; of the trees cut, 90% of the stem wood was harvested and moved off-site. This thinning plan resulted in 35% of all cells thinned (many of them twice) between 1994 and 2100. LSR lands had no timber harvest.

(5) Conservation with Fire Restoration Scenario (Cons + fire)

The logging regime in this scenario is the same as in the *Cons – fire Scenario* above but the fire regime was projected to return to the pre-suppression level (200-year fire return interval) starting in 1994. This scenario was designed to assess the impact of restoring the natural/pre-settlement fire regime as part of conservation-oriented forest management.

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[2] Abbreviated name of scenario in parenthesis

These five management scenarios involved ten different disturbance treatments across three land-use allocations (Table 2). Fire restoration was included in all three treatments of the *Cons+fire Scenario*, whereas fire suppression was applied in all other treatments. Therefore in further narrative different treatments were generally identified by harvest prescriptions only, with fire suppression mentioned as needed for clarity. For each treatment, the LANDCARB model output represented average per-ha C stores in all simulated C pools in each year of simulation between 1850 and 2100 in a landscape composed of 400 individual stands (cells) where historic disturbance and appropriate future fire and harvest treatments were applied (Table 2, Fig. 4, 6). Landscape-level net C balance was calculated as the change in total C store between two consecutive years of the simulation (Fig. 5). The landscape-level average values of C store and net C balance were multiplied by land area in respective land-use allocations in OR and WA (Table 1) and summed across all allocations to calculate state-level and regional (OR+WA) totals of C stores and annual net C balance for each scenario (Fig. 7-9, Table 3). The state and regional-level averages (Fig. 10 and in text) are the LANDCARB simulation results weighted by the areas of relevant land-use allocations in OR and WA (Table 1). All C totals and averages include C in wood products and in disposal (landfills) unless a sub-set of C pools is specified.

3. Results

Future dynamics of ***landscape-level average C stores on different land use allocations*** varied by treatment (Table 2, Fig. 4). On AW/CR lands, C stores increased over time and fire suppression led to higher average C stores than fire restoration (Fig. 4). The difference between the two treatments was small, but it increased over time and in 2100 reached 14.0 and 14.6 MgC ha^{-1} in OR and WA, respectively. On LSR lands the no-harvest treatment with and without fire suppression resulted in a similar pattern of increase in C stores over time, whereas the 60-year rotation treatment caused the average C stores to decline by 84 MgC ha^{-1} between 1993 and 2100 (Fig. 4). Most of the loss under the 60-year rotation treatment occurred early in the projection period; after 2060 in OR and after 2040 in WA C stores became relatively stable. The difference in average C stores on LSR lands between the 60-year rotation treatment and the no-harvest treatment became stable by year 2100 at 175 MgC ha^{-1} in OR and 185 MgC ha^{-1} in WA.

On Matrix lands (Fig. 4), combined fire suppression and thinning treatments resulted in greater increase of the average C store by year 2100 than all other treatments: from 323 to 451 MgC ha^{-1} in OR and from 339 to 481 MgC ha^{-1} in WA. Harvest on a 200-year rotation with fire suppression produced a smaller increase in C stores (from 323 to 391 MgC ha^{-1} in OR and from 339 to 417 MgC ha^{-1} in WA by 2100) while the 120-year rotation increased C stores on Matrix lands only slightly (from 323 to 340 MgC ha^{-1} in OR and from 339 to 362 MgC ha^{-1} in WA) after a small initial decline. Of the 5 treatments considered for Matrix lands (Table 2), harvest on a 60-year rotation led to the lowest C stores on Matrix lands (284 MgC ha^{-1} in OR and 302 MgC ha^{-1} in WA by 2100). Thus, Matrix lands were a net sink of C over the entire projection period under treatments that included thinning (with and without fire suppression) or harvest at 200-year rotation with fire suppression. If the harvest were conducted on a 120-year rotation then the net C balance on Matrix lands would remain close to zero and under a 60-year rotation Matrix lands were projected to be a net source of C for several decades, then approach zero net C balance around year 2060 (Fig. 5).

The composition of C stores differed substantially among treatments with differences increasing over the projection time. The greatest differences were on Matrix lands (Fig. 6): by year 2100 under the 200-year rotation treatment live tree biomass on Matrix lands averaged 156 MgC ha^{-1} in OR and 162 MgC ha^{-1} in WA (38-39% of the total C store) whereas under the 60-year rotation treatment live biomass averaged ~67 MgC ha^{-1} (both in OR and WA; 22-24% of total C store). The highest C store in wood products and disposal (53 and 54 MgC ha^{-1} in OR and WA, respectively) resulted from the 60-year harvest rotation on Matrix lands (Fig. 6). This was a significant proportion of total C store associated with each hectare of Matrix lands (about 18% in 2100), while other scenarios resulted in much lower C store in wood products and disposal. C accumulation in wood products and disposal pools under 60-year rotation treatment on Matrix lands made up for only a small fraction of C lost from live and dead biomass pools resulting in a lower total C store by 2100 than under other treatments (Fig. 6).

Changes in state-level total C stores in western OR and WA under different management scenarios (Fig. 7) reflected the combined effect of changes in per-ha average C stores described above and the forest land area in each land-use allocation (AW/CR, LSR and Matrix) within the states (Table 1). The total C store was higher in OR in part because the total forest area included was 18% (437 thousand ha) greater than in WA (Table 1). The differences among scenarios were also greater in OR because future timber harvest prescriptions applied only to LSR and Matrix lands which together accounted for 81% of federal forest land area in OR but only 47% in WA. The federal forest lands transitioned from a net source to a net sink of C in the early 1990s in OR and in the late 1990s in WA and remained a net sink in both states through 2100 for all examined scenarios except the *Industry Scenario* (Fig. 8). The *Industry Scenario* was projected to extend the duration of the historic C source until nearly 2060 in OR and 2020 in WA.

The role of different C pools in the overall state-level net C balance changed over time and the differences among scenarios were substantial (Fig. 9). The live biomass pool was initially responsible for most of the C sink under the *NWFP* and *Conservation* scenarios, while there were small net losses in dead mass and products/disposal pools. For example, in the *NWFP-i Scenario* (Fig. 9), the role of live biomass declined over time while the role of dead, stable, and products/disposal pools increased. This demonstrates the importance of adequate accounting for all these C pools, not just live biomass. Towards the end of the projection period, the net gains in live biomass represent less than half of the estimated total C sink. The pattern of net C gains and losses was very different in the *Industry Scenario* where net gains in products/disposal pools declined over time and net losses were initially associated mainly with live biomass, but dead C store eventually declined as well (Fig. 9).

Implementation of the NWFP was projected to result in a significant and long-lasting ***net increase in total C stores on federal forest lands relative to the 1993 level*** (Table 3). This increase was projected for all land-use allocations but it was relatively small on AW/CR lands where management prescriptions were not changed by the plan, and was much greater on LSR and Matrix lands (Fig. 4). If the low initial levels of timber harvest on lands under the NWFP were extended into the future *(NWFP-i Scenario),* a significant net increase in C stores is projected for both OR and WA (Table 3). If intensive timber harvest continued as projected under the *Industry Scenario,* the total C stores on federal forest lands would have remained lower than in 1993 throughout the projection period in OR whereas in WA C stores would have returned to the initial (1993) level towards the end of the projection period in 2100 (Table 3, Fig.

7). Between 1993 and 2100 the net changes in C stores in wood products and disposal were generally smaller than changes on-site (Table 3). The net increase in wood products C was projected only for the *Industry Scenario* in OR while in all other scenarios C stores in disposal (landfils) increased between 1993 and 2100. In all scenarios except the *Industry Scenario* the annual rate of C accumulation increased in the beginning of the projection period, reached maximum between 2005 and 2020 approaching 4 TgC yr^{-1} in OR and 2.3 TgC yr^{-1} in WA, then gradually declined (Fig. 8).

If the *Industry Scenario* (rather than initial C store in 1993) was used as a baseline for evaluating forest management alternatives, then the effect of the *NWFP and Conservation scenarios* was greater, especially in the beginning of the projection period (Fig. 7-9). In comparison with the *Industry Scenario,* the impact of the *NWFP-i Scenario* on total C stores between 1993 and 2010 was 86.0 TgC (5.1 TgC yr^{-1} or 2.16 MgC ha^{-1}yr^{-1}) in OR; in WA the respective values are 45.2 TgC (2.66 TgC yr^{-1} or 1.33 MgC ha^{-1} yr^{-1}; from Table 3).

Scenario selection had a large impact on C removal with timber harvest: *Conservation scenarios* generated 2-4% and *NWFP scenarios* 17-40% of the timber removals under the *Industry Scenario* over the entire projection period (Table 3). The differences in these and other state-level impacts of alternative management scenarios were moderated in WA by a relatively large proportion of forest lands in AW/CR land use allocation (Table 1).

The area of old-growth forest in OR is projected to decline under the NWFP from nearly 32% in the early 1990s to 22-25% by 2050 and remain fairly stable in the subsequent 50 years (Tables 1,3; Fig. 3). The *Industry Scenario* reduced old-growth area in OR even further (to 7.6%) and only *Conservation scenarios* were projected to maintain the 1990s area of old-growth in OR. In WA however, the NWFP (both as implemented and as planned) and the *Cons+fire* scenario maintained the initial proportion of old-growth, while the *Cons-fire Scenario* moderately increased old-growth area by 2100 (Table 3). Interestingly, the proportion of old-growth on federal forest lands maintained by the *Industry Scenario* in WA was similar to that achieved by the NWFP in OR.

4. Discussion

The scenarios examined represent, in a generalized form, different visions of future management of forests in the PNW. These scenarios allow one to gauge the range of possible outcomes associated with a set of diverse management paradigms. The five scenarios applied to two states with very similar forest types, broadly comparable land use histories and small but significant differences in allocation of federal forest lands to different land-use categories produced distinct patterns of change in C stores and net C balance with clear differences among scenarios (Fig. 7-9). The NWFP represented a major shift in management of federal forest lands and over time it appears to have increased C stores dramatically in comparison to 1993 and even more so relative to a baseline of reverting to higher timber harvests of the 1980s (Table 3, Fig. 7-9). The reduced levels of timber harvest on federal forest lands in the early 1990s ended the period of net losses of C from federal forests that was estimated to last over 50 years. At the start of the NWFP these forests were close to a point of balance in C exchange between forests and the atmosphere in OR whereas in WA the point of balance was reached a few years later (Fig. 8). In WA, the relatively large proportion of lands in the AW/CR category (Table 1) where the management prescriptions of the NWFP did not apply diminished the differences in state-level impacts among alternative management scenarios (Fig. 7-9). In both states the difference between the *Industry Scenario* and the four other scenarios was far greater than the differences among the remaining four scenarios (two *NWFP* and two *Conservation scenarios)* that restricted timber harvest to varying degrees.

Comparison with other published estimates of C pools and flux in OR and WA is difficult because of differences in land base and C pools considered. For 8.2 million ha of forest land in western OR, Law et al. (2004) estimated a net C sink of 8.2 TgC yr^{-1} or 1.0 MgC ha^{-1} yr^{-1} in 1995-2000 with C accumulation in forest products responsible for 17% of this sink. The state-wide estimate by Turner et al. (2011) for 2000-2005 is 1.10 MgC ha^{-1} yr^{-1} and includes only on-site C (no forest products or disposal). Our estimate of an average annual rate for OR of 0.91 MgC ha^{-1} yr^{-1} in 1994-2010 (Table 3) is generally in line with the above estimates but our simulations indicate that during this period forest products were losing (Fig. 9) rather than accumulating C as reported by Law et al. (2004). By accounting only for the fate of C harvested during 1995-2000, the Law et. al (2004) study ignores losses from the wood products pool that was in large part generated by peak harvests in earlier years. The LANDCARB model used in this study tracks the legacies of past forest disturbance including C in products and disposal. This likely explains the difference in the assessment of the role of forest product pools.

To better align the scope of C estimates based on Biome-BGC modeling (Law et al. 2004, Turner et al. 2007, 2011) and our results we compared our estimate for net change in C pools on-site (excluding products/disposal) during 1996-2000 with a sub-set of NBP estimates used in Turner et al. (2007) for the same land base and time interval (D. Turner, pers. comm., Fig. 10): the average LANDCARB estimate is 0.74 MgC $ha^{-1}yr^{-1}$ vs. 1.24 MgC ha^{-1} yr^{-1} estimated by Biome-BGC. Interestingly, in the LANDCARB estimation the net increase in live forest biomass C of 1.01 MgC ha^{-1} yr^{-1} is partially offset by 0.25 MgC ha^{-1} yr^{-1} losses from dead plant material and soil C. The disagreement between the two models likely stems from difference in model treatment of C in dead and soil pools: Biome-BGC outputs suggest that those components are changing in proportion to live biomass (e.g., Turner et al. 2007) whereas in LANDCARB live and dead biomass pools are not synchronized – they are linked functionally and often change out of phase with each other reflecting the legacies of past disturbances (Fig. 9). Furthermore, the two models represent different aspects of C dynamics on forest lands – Biome-BGC outputs clearly reflect year-to-year fluctuations in C flux driven by weather variations while LANDCARB outputs reflect change in C stores over years and decades in response to changing management and natural disturbance regimes (Fig. 10).

Conservation and restoration of old-growth forest and associated species in the PNW was the primary objective of the NWFP and initial analysis of its effects concluded that the goals set for the plan were met or exceeded (Mouer et al. 2005, Rapp et al. 2008), even though there was evidence of net decline in old-growth forest area (Davis et al. 2011, Ohmann et al. 2012). Our analysis examined longer-term trends and therefore is not directly comparable but it suggests that over the long term the protections under the NWFP are sufficient to maintain and in part restore old-growth forest in WA but not in OR (Table 3). Several factors contribute to differences in the impact of NWFP scenarios on old-growth area in OR and WA and the high proportion of Matrix lands in OR is a major factor – they occupy 41.5% of federal forest lands, a proportion 2.6 times greater than in WA. The planned harvest approximated by rotation of 120 years (*NWFP-p Scenario)* can over time virtually eliminate the old-growth on Matrix lands in both OR and WA.

The projected losses are especially great in OR where Matrix lands contained a large area of old-growth forest at the start of the NWFP (267.1 thousand ha or 27.4% of all old-growth in OR; Table 1). The forest land area protected from clearcut harvest under the NWFP (AW/CR plus LSR) is too small in OR to maintain the early 1990s area of old-growth in this state but in WA the protected area is large enough (84.1%, Table 1) to compensate for the loss of old-growth on Matrix lands. In addition, the area of forest in the Mature age group is very small on AW/CR and LSR lands in OR (Table 1) and this limits the recruitment of old-growth forest during most of the ~100 year projection period.

The management of federal forest lands under the NWFP was not intended to increase C stores, yet this outcome was achieved very quickly and effectively (Fig. 7). Other publications also conclude that the potential of forests in the PNW to store additional C is exceptionally high (e.g., Harmon et al. 2004, Foley et al. 2009, Pan et al. 2011). Longer harvest rotations on Matrix lands combined with no harvest on other land-use allocations can be expected to maintain high rates of C sequestration on federal forest lands for many decades (Table 3, Fig. 8-9). In comparison to the two *NWFP scenarios* the additional C sequestration under *Conservation scenarios* is either moderate in OR or small to non–existent in WA (Fig. 7, 8). However, clearcut harvest even at the low rate allowed under the NWFP can essentially eliminate old-growth from forest lands allocated to rotation-based management (e.g., Thompson et al. 2006). To offset this loss and maintain old-growth at the state level a very large set-aside area is required (e.g., 84% in WA). Thus, forest management for timber production with long harvest rotations appears to be generally compatible with the goal of C sequestration on forest lands, but old-growth conservation may not be possible on the same land base.

Conservation scenarios for both states, with and without fire restoration, are projected to maintain and slightly increase the area of old-growth by approximately 2050 (Fig. 3, Table 3). The management aimed at old-growth restoration represented by the *Conservation scenarios* is fully compatible with the goal of C sequestration at the time-scale of decades examined in this study, but there is a major difference in time needed for achieve these goals. Old-growth restoration takes much longer: in our simulations for the *Conservation scenarios* the peak increases in C stores occurred within a few years after the change in management while the area increase of old-growth age class only began in the 2050-2100 time period (Fig. 7-9).

The potential role of forest management in state-level climate change mitigation efforts is greater in the PNW than in most other regions. Considering that the annual fossil fuel emissions in OR are about 15 TgC yr^{-1} (http://oregon.gov/energy/GBLWRM/Pages/Oregon_Gross_GhG_Inventory_1990-2008.aspx, last visited April 27, 2012), the average estimated net increase in total C stores on federal forest lands between 2010 and 2025 under *NWFP-i Scenario* (2.49 TgC yr^{-1}, Fig. 9) is equivalent to 16.6% of state fossil fuel emissions. The average estimated net losses of C from forest lands under the *Industry Scenario* during this time interval are equivalent to adding 2.17 TgC yr^{-1} or 14.5% to state-level fossil fuel emissions. Current state-level accounting of C emissions does not include forests and other ecosystems even though forest management policies in OR control a substantial portion of state-level C emissions. Greater timber production under *Industry Scenario* (Table 3) is unlikely to substitute alternative energy-intensive materials because the ability (or willingness) of consumers to substitute softwood lumber in response to restricted supply proved to be very limited (Adams et al. 1992). However, increased timber production elsewhere is likely (Alig. et al. 2006, Wear and Murray 2004) and this “leakeage” needs to be addressed in designing climate change mitigation policies (Nabuurs et al. 2007).

Over time the annual net C balance values converge at zero for all management scenarios (Fig. 8) as can be expected if management remains constant (Krankina and Harmon 2006). However, this does not indicate a similarity of outcomes for atmospheric C: state-level C stores are much lower under the *Industry Scenario* than under both NWFP scenarios (Fig. 7, Table 3) and this difference reflects the amount of C that has been removed from the atmosphere and remains sequestered on land as a result of change in forest management under the NWFP.

5. Uncertainties and Limitations

This study exploits the strength of LANDCARB in assessing change in forest C stores given past disturbance regime and future management scenarios. The impact of product substitution or the use of wood for bioenergy on C balance was not simulated and was not included in scenario comparisons. Many of the currently available and commonly used methods for calculating the substitution effect cause overestimates (O’Hare et al. 2009, Law and Harmon 2011, Mitchell et al. 2012). Recent research improved methods of estimating the effect of wood-based bioenergy on atmospheric C and showed the need to re-assess the earlier estimates that did not fully account for C emissions associated with biofuels and therefore were overly optimistic (e.g., O'Hare et al. 2009, Hudiburg et al. 2011). The effect of product substitution is commonly estimated by applying a “displacement factor” to the amount of C transferred to wood products when they are used in place of other more energy-intensive materials (e.g., Hennigar et al. 2008). However, the use of displacement factors as a measure of C emission reduction resulting from each and every piece of wood used is potentially a misrepresentation of substitution effect (Sathre and O’Connor 2010). The extent of wood substitution for other materials in response to future changes in timber harvest on federal forest lands in the NWFP area is likely low because during similar past reductions in timber supply and associated price increases the consumers were unwilling to substitute softwood lumber (the main wood product in the region) for other products (Adams et al. 1992). Thus, including product substitution is unlikely to influence our overall assessment of differences among management scenarios. The impact on forest management in other land ownerships in the PNW region and other timber-producing regions is likely (e.g., Alig et al. 2006, Wear and Murray 2004) but was not examined in this study.

The LANDCARB model projections represent average values of C stores in forest stands of different ages within the NWFP area in two states and do not reflect ecological complexities and variability within the study area or possible adaptation of management prectices to diverse site conditions. No socio-economic drivers or climate change impacts are considered either and therefore the results are to be interpreted as a comparative assessment of changes in C stores in response to different forest management paradigms rather than likely future dynamics. More realistic quantitative projections of future C balance that reflect the diverse impacts of climate change on forest ecosystems and socio-economic factors that shape the land-use policies in the region require a new research effort to integrate the available forest models.

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Table 1. Area of aggregated land use allocations and age groups of forest stands on federally managed lands in the Northwest Forest Plan area in early 1990s (after Mouer et al. 2005; thousand ha)

Land use allocations[1]	Age groups				Total (%)
	Very Young	Young	Mature	Old-Growth	
Western Oregon					
AW/CR	74.6	166.7	32.1	164.7	438.1 (18.7)
LSR	280.8	173.3	141.4	337.2	932.7 (39.8)
Matrix	346.6	229.2	131.8	267.1	974.7 (41.5)
Total (%)	702.0 (29.9)	569.2 (24.3)	305.3 (13.0)	769.0 (32.8)	2345.5 (100)
Western Washington					
AW/CR	334.9	173.0	173.3	377.9	1059.0 (53.0)
LSR	188.4	137.7	97.0	197.6	620.7 (31.1)
Matrix	129.9	82.9	43.5	62.7	318.9 (15.9)
Total (%)	653.2 (32.7)	393.6 (19.7)	313.8 (15.7)	638.2 (31.9)	1998.6 (100)

[1] Administratively Withdrawn/ Congressionally Reserved (AW/CR); Late-Successional Reserves (LSR)

Table 2. Management scenarios for federal forest lands in the Northwest Forest Plan area (see descriptions in text for details).

#	Land use allocation[1]	Treatments		Management scenarios				
		Harvest	Fire suppression	1. Industry	2. NWFP-plan	3. NWFP-implemented	4. Conservation with fire suppression	5. Conservation with fire restoration
1	AW/CR	no	yes	X	X	X	X	
2		no	no					X
3	LSR	60-yr rotation	yes	X				
4		no	yes		X	X	X	
5		no	no					X
6	Matrix	60-yr rotation	yes	X				
7		120-yr rotation	yes		X			
8		200-yr rotation	yes			X		
9		thinning only	yes				X	
10		thinning only	no					X

Table 3. Selected metrics of projected impact of management scenarios on C stores and area of old-growth forest.

Scenario	Change in total C store[1] since 1993, TgC				Average annual rate in 1994-2010, MgC ha^{-1}yr^{-1}	Wood harvested in 1994-2100, TgC	Change between 1993-2100, TgC			% old-growth area in 2100
	2010	2025	2050	2100			On-site	Products in use	Disposal	
Western Oregon										
Industry	-49.7	-82.2	-96.3	-87.0	-1.25	307.5	-155.2	21.7	46.4	7.6
NWFP-p	22.5	46.8	84.5	129.3	0.56	121.9	113.0	-3.2	19.4	21.7
NWFP-i	36.3	73.5	123.3	179.0	0.91	74.7	176.4	-10.1	12.6	22.1
Cons-fire	49.8	101.9	169.4	237.6	1.25	6.8	256.1	-21.6	3.0	33.3
Cons+fire	46.1	94.6	152.4	205.8	1.16	7.3	224.2	-21.5	3.1	30.2
Western Washington										
Industry	-26.9	-28.8	-18.0	5.4	-0.79	154.0	-17.4	-2.0	24.8	21.6
NWFP-p	13.4	44.6	89.5	139.0	0.39	41.8	148.4	-17.9	8.5	31.5
NWFP-i	18.3	53.5	102.4	156.7	0.54	26.3	170.6	-20.2	6.3	31.7
Cons-fire	22.8	63.3	118.1	176.8	0.67	5.7	197.1	-23.7	3.4	35.1
Cons+fire	19.3	56.6	103.0	148.0	0.57	5.9	168.3	-23.7	3.4	31.9

[1] Total store includes C on-site, in wood products and disposal.

Figure captions.

Figure 1. Study area in Western Oregon and Western Washington with boundaries of counties. FIA data from shaded counties were used to calibrate the LANDCARB model.

Figure 2. Results of LANDCARB model calibration with FIA data for Western Oregon (OR) and Western Washington (WA): live biomass change with age of forest stands.

Figure 3. Proportions of federal forest area in different age groups: at the start of NWFP (early 1990's; Observed) and projected to 2050 under different management scenarios for Western Oregon (OR) and Western Washington (WA).

Figure 4. Historic and projected future carbon stores under different management treatments on NWFP land use allocations in Western Oregon: AW/CR, LSR, and Matrix (see treatment specifications in Table 2 and Methods text).

Figure 5. Historic and projected future annual net carbon balance on Matrix lands under different management treatments in Western Oregon and Western Washington (positive values represent net gains; negative values represent net losses of carbon to the atmosphere).

Figure 6. Composition of carbon stores on Matrix lands in Western Oregon under three management treatments.

Figure 7. Historic and projected future change in C stores under alternative management scenarios – totals for all land-use allocations combined in Western Oregon (OR) and Washington (WA).

Figure 8. Annual net carbon balance on federal forest lands between 1900 and 2100 under different management scenarios in Western Oregon and Western Washington (positive values represent net gains; negative values represent net losses of carbon to the atmosphere).

Figure 9. Average periodic rate of total C stock change (line) and change in different C pools (vertical bars) under *NWFP-i Scenario* and *Industry Scenario* in Western Oregon and Western Washington. Positive values represent net gains; negative values represent net losses.

Figure 10. Comparison of annual C balance estimates for federal forest lands in Western Oregon by two models: LANDCARB and Biome-BGC. LANDCARB estimates are net annual changes in total C store on site; Biome-BGC estimates are Net Biome Production (simulated NEP adjusted for wildfire emissions and timber harvest; Turner et al. 2007; data subset – Turner, pers. comm.).

Appendix: Key Parameters of LANDCARB Model

Appendix Table 1. Parameter values for tree establishment, growth, mortality and decomposition.

Parameters (units)	Douglas-fir	Western Hemlock
Tree Establishment		
$\text{Light}_{\text{Max}}$ (fraction of full sunlight)	1.00	0.90
$\text{Light}_{\text{Min}}$ (fraction of full sunlight)	0.90	0.02
Soil $\text{water}_{\text{Max}}$ (Mpa)	-0.1	-0.05
Soil $\text{water}_{\text{Min}}$ (Mpa)	-2.0	-1.7
Growth		
Light compensation point (%)	5	2
Light extinction coefficient ($\text{ha}\cdot\text{Mg}^{-1}$)	0.15	0.20
Foliage increase rate_{Max} (dimensionless)	1.00	0.60
Fine root/foliage ratio (dimensionless)	0.33	0.33
Branch/bole ratio (dimensionless)	0.50	0.50
Coarse root/bole ratio (dimensionless)	0.496	0.52
Wood respiration rate_{Max} (year^{-1}) [A]	0.017	0.017
Rate of heartwood formation (year^{-1})	0.05	0.02
$\text{Height}_{\text{Max}}$ (m)	90	85
Mortality		
Tree mortality $_{\text{Max}}$ (year^{-1})	0.015	0.015
Branch prune $_{\text{Max}}$ (year^{-1})	0.020	0.020
Coarse root prune $_{\text{Max}}$ (year^{-1})	0.005	0.005
Tree age $_{\text{Max}}$ (year^{-1})	800	700
Foliage turnover rate (year^{-1})	0.20	0.25
Fine root turnover rate $_{\text{Max}}$ (year^{-1})	0.50	0.50
Decay Rates [B]		
Foliage (year^{-1})	0.20	0.17
Fine root (year^{-1})	0.15	0.15
Branch (year^{-1})	0.07	0.08
Coarse root (year^{-1})	0.07	0.10
Sapwood (year^{-1})	0.05	0.05
Heartwood (year^{-1})	0.02	0.05
Transfer rates to stable pools (both species) [C]		
Dead foliage (year^{-1})	0.0490	
Dead fine root (year^{-1})	0.0731	
Dead branch (year^{-1})	0.0099	
Dead coarse root (year^{-1})	0.0342	
Snag sapwood (year^{-1})	0.0430	
Snag heartwood (year^{-1})	0.0240	
Log sapwood (year^{-1})	0.0277	
Log heartwood (year^{-1})	0.0148	

[A] Optimum respiration temperature is 45°C; Q_{10} is 2.0 (dimensionless)

[B] Base rates at 10°C; Q_{10} is 2.0 (dimensionless)

[C] Decay rates for stable foliage, wood, soil, and buried charcoal are 0.100, 0.25o, 0.007, 0.002 (year^{-1}), respectively.

Appendix Table 2. Forest product parameter values (range in values reflects changes in parameter values over time).

Parameters (units)

Manufacturing	Structural Wood	External Bioenergy	Pulp Wood
Log allocation (%)	93 – 99	0 – 2	1 – 5

Product Use	Allocation (%)	Disposal (year^{-1})	Decomposition (year^{-1})	Recycling (%)
Long term structure	75	0.010 – 0.015	0.010 – 0.015	1 – 10
Short term structure	25	0.10 – 0.20	0.10	0 – 10
Paper	n/a	0.30 – 0.40	0.30	0 – 30
Mulch	n/a	n/a	0.10	n/a

Disposal	Allocation (%)	Combustion (year^{-1})	Decomposition (year^{-1})
Open dump	1 – 100	0.3	0.30
Landfill	0 – 89	0.0	0.005
Incineration without energy recovery	0 – 10	1.0	n/a
Incineration for energy recovery	0 – 5	1.0	n/a

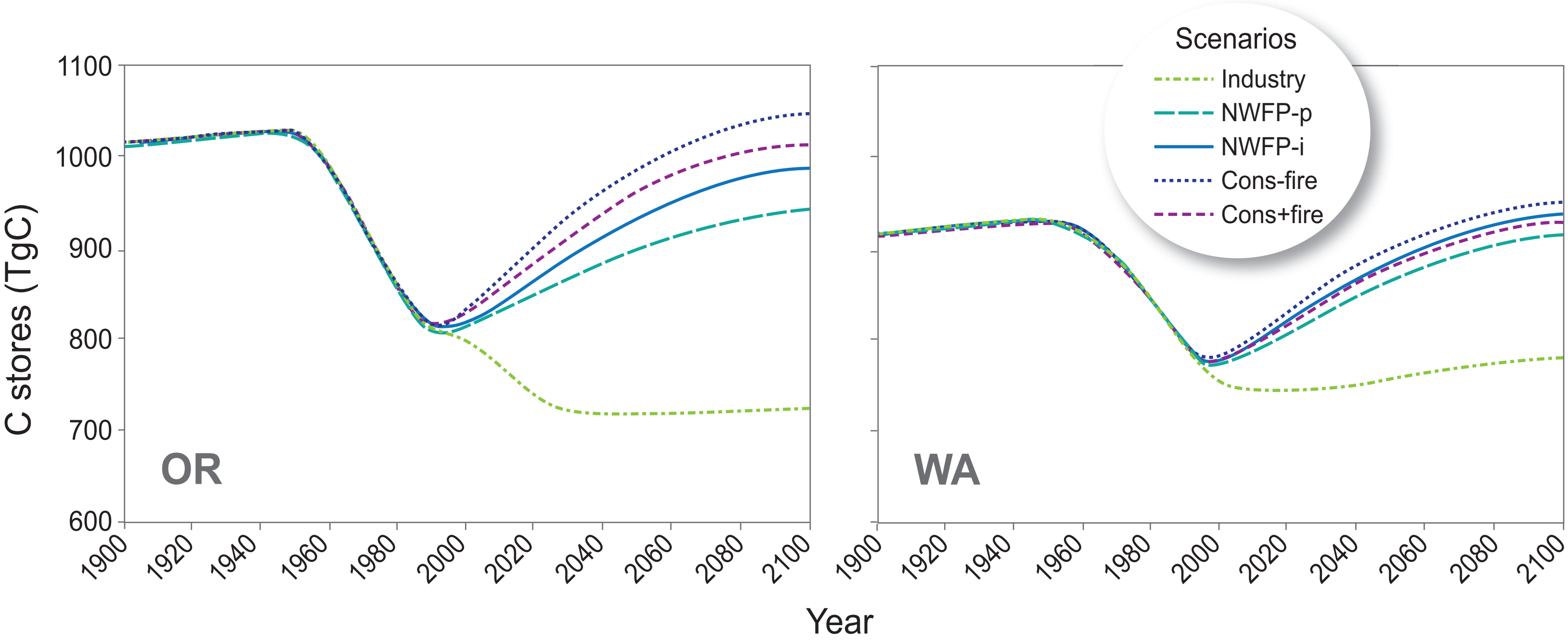
Appendix Table 3. Fire impact on live mass: percent of live mass that is killed by fire (*%Killed*); percent of the %Killed that is burned off (lost to the atmosphere; *%Burned*); percent of the %Killed that is converted to charcoal (*%Charcoal). Above* refers to above ground mass, *Below* refers to below ground mass. *LTree* is lower tree; *UTree* is upper tree. Note: all wildfires were assummed to be hot (high severity)

Layer	%Killed		%Burned		%Charcoal	
	Above	Below	Above	Below	Above	Below
Herb	100	100	99.5	50	0.5	1.0
Shrub	100	100	99	10	1.0	1.0
LTree	100	100	10	5	2.0	1.0
Utree	100	100	5	2	4.0	1.0

Appendix Table 4. Fire impact on dead mass. Note: all wildfires were assummed to be hot (high severity); the severity of prescribed burning of dead material left after clearcut harvest varied.

Detrital Pool	Fire Severity Light	Medium	Hot
Percent of dead mass remaining after fire			
Dead foliage	75.0	50.0	0.0
Dead fine roots	100.0	75.0	25.0
Snag sapwood	100.0	85.0	50.0
Log sapwood	95.0	75.0	10.0
Snag heartwood	100.0	95.0	75.0
Log heartwood	100.0	90.0	50.0
Dead branches	75.0	50.0	5.0
Dead coarse roots	100.0	90.0	50.0
Stable soil	100.0	100.0	100.0
Stable foliage	100.0	50.0	5.0
Stable wood	100.0	50.0	5.0
Charcoal	10.0	5.0	0.0
Percent of dead mass converted to charcoal by fire			
Dead foliage	2.0	3.0	0.0
Dead fine roots	1.0	2.0	0.0
Snag sapwood	1.0	1.7	2.5
Log sapwood	2.0	3.5	5.0
Snag heartwood	0.0	0.0	1.2
Log heartwood	0.0	0.4	1.5
Dead branches	5.0	10.0	1.0
Dead coarse roots	0.5	1.0	2.0
Stable soil	0.0	0.0	0.0
Stable foliage	2.0	3.0	1.0
Stable wood	2.0	3.0	1.0

Graphical Abstract (for review)



CARBON BALANCE ON FEDERAL FOREST LANDS OF WESTERN OREGON AND WASHINGTON:

THE IMPACT OF NORTHWEST THE FOREST PLAN

Olga N. Krankina[a], Mark E. Harmon[a], Frank Schnekenburger[a], Carlos A. Sierra[ab]

Highlights

Highlights

- Model projected forest carbon stores in Oregon and Washington to year 2100
- Carbon stores and patterns of change over time differed under alternative management scenarios
- Continuation of the Northwest Forest Plan was projected to increase carbon stores
- Return to high levels of timber harvest was projected to reduce carbon stores
- Current management allows conservation of old-growth forest in Washington but not in Oregon

Figure1

Figure2

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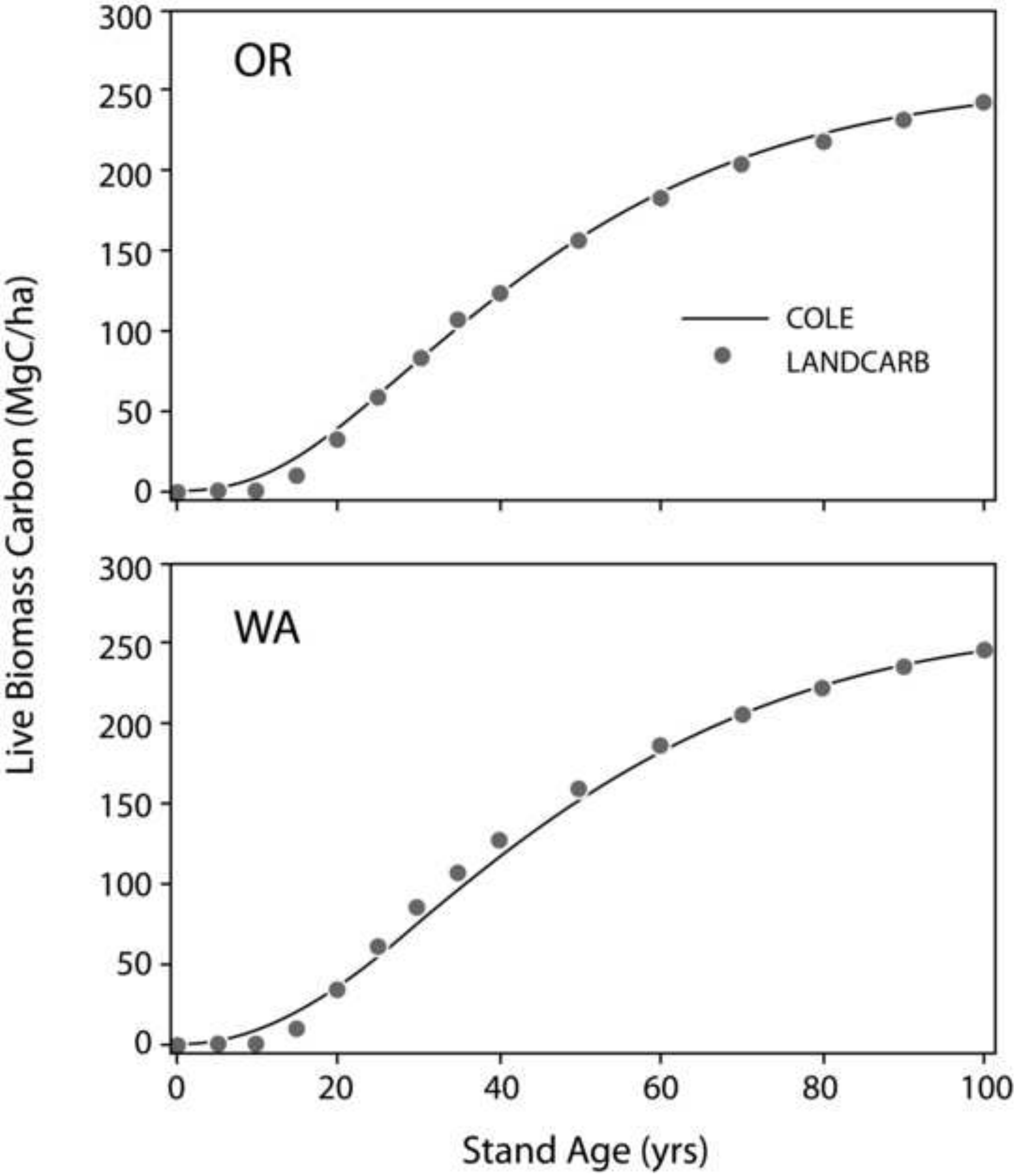
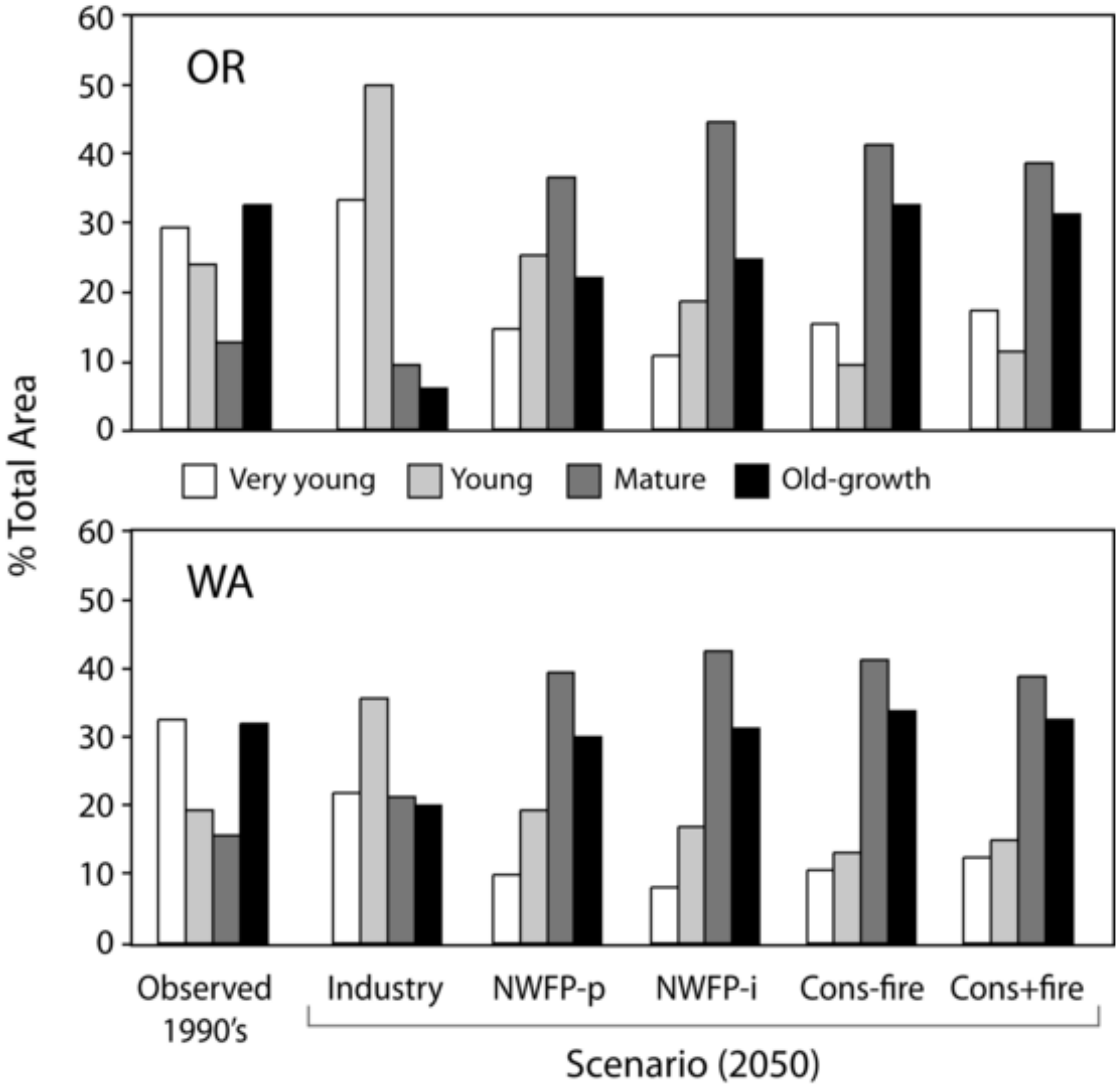


Figure3



60
50
40
30
20
10
0
OR
Very young
Young
Mature
Old-growth
% Total Area
WA
Observed 1990's
Industry
NWFP-p
NWFP-i
Cons-fire
Cons+fire
Scenario (2050)

Figure4

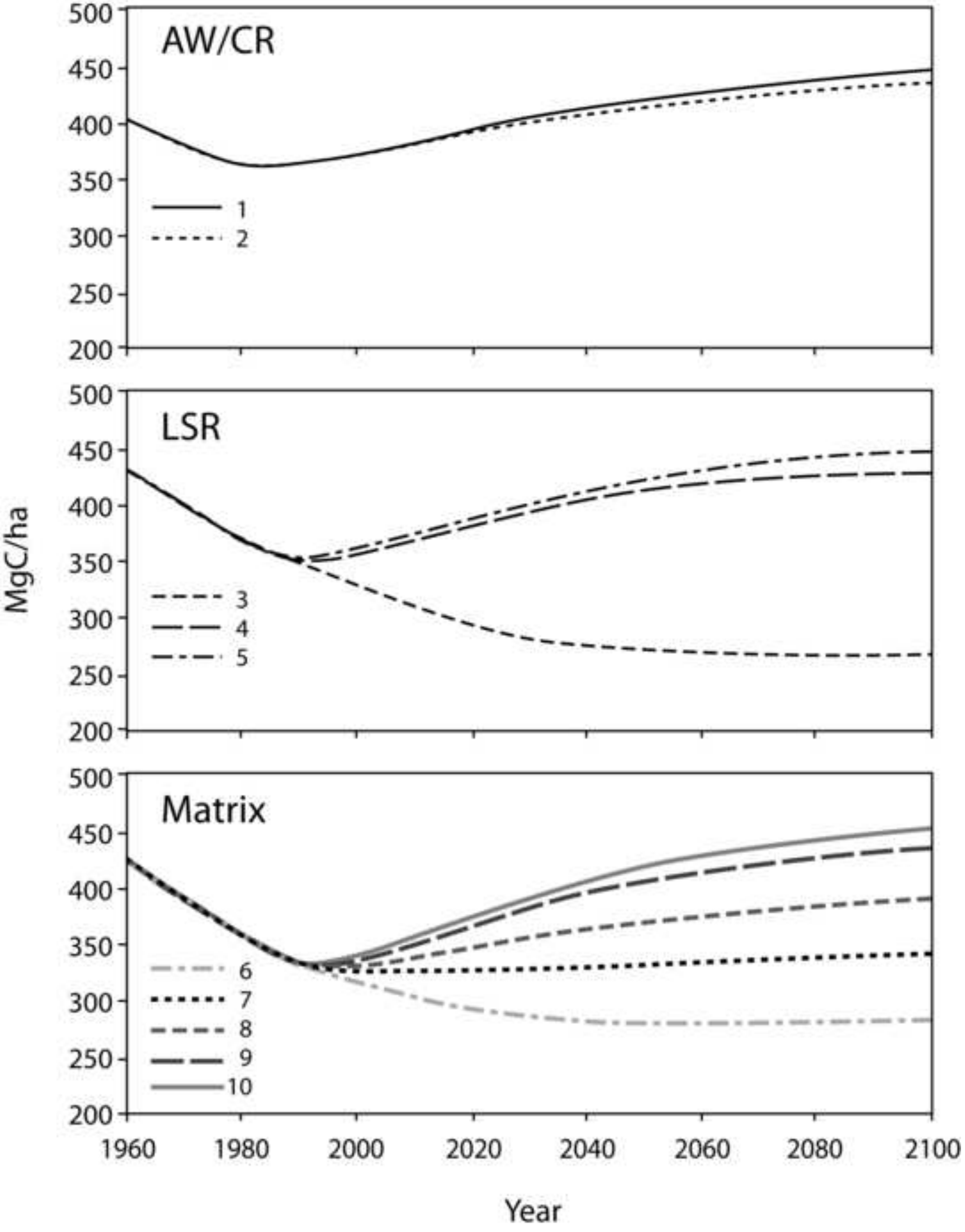

AW/CR
1
2
LSR
3
4
5
Matrix
6
7
8
9
10
MgC/ha
500
450
400
350
300
250
200
1960
1980
2000
2020
2040
2060
2080
2100
Year

Figure5

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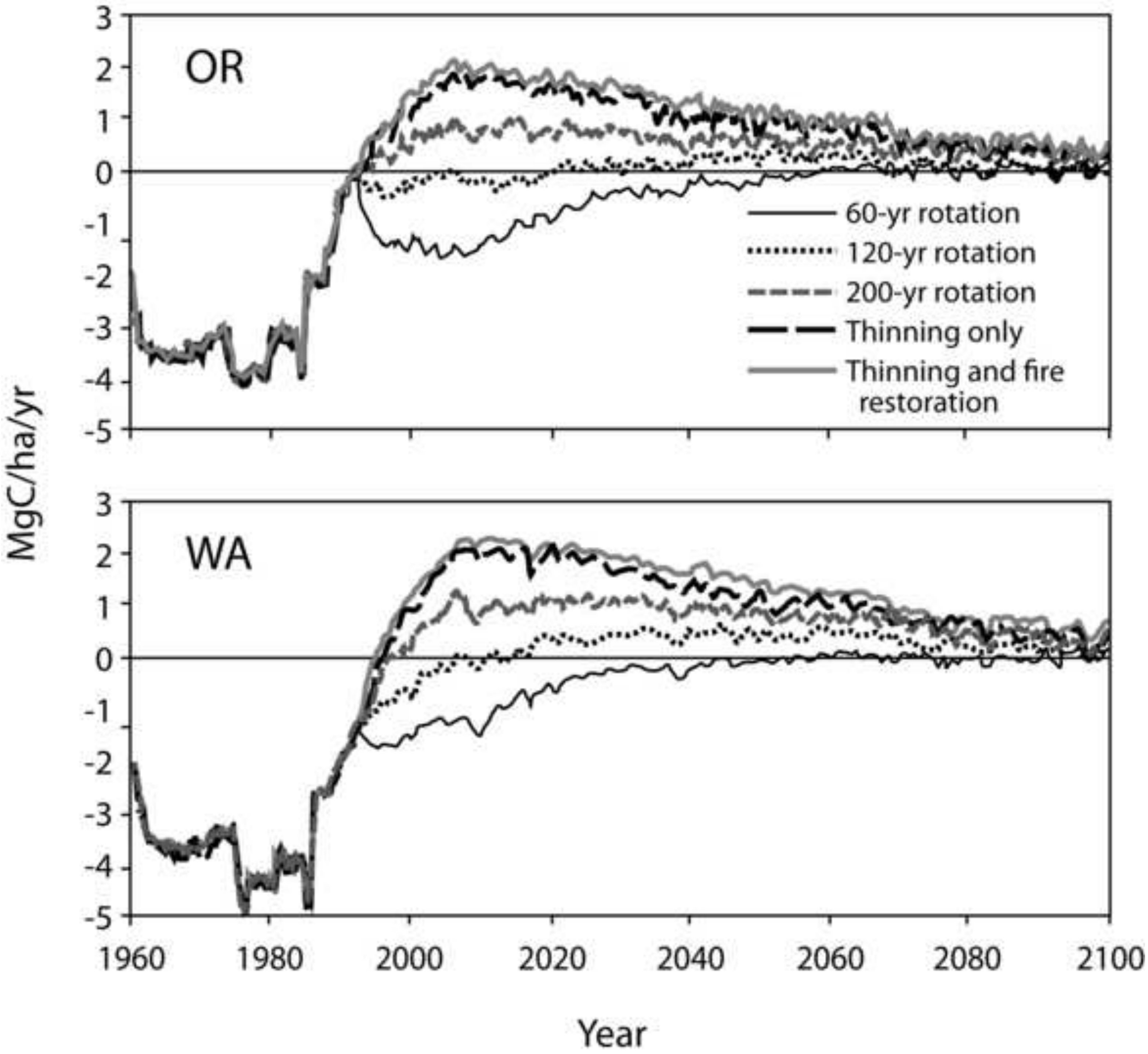

Figure6

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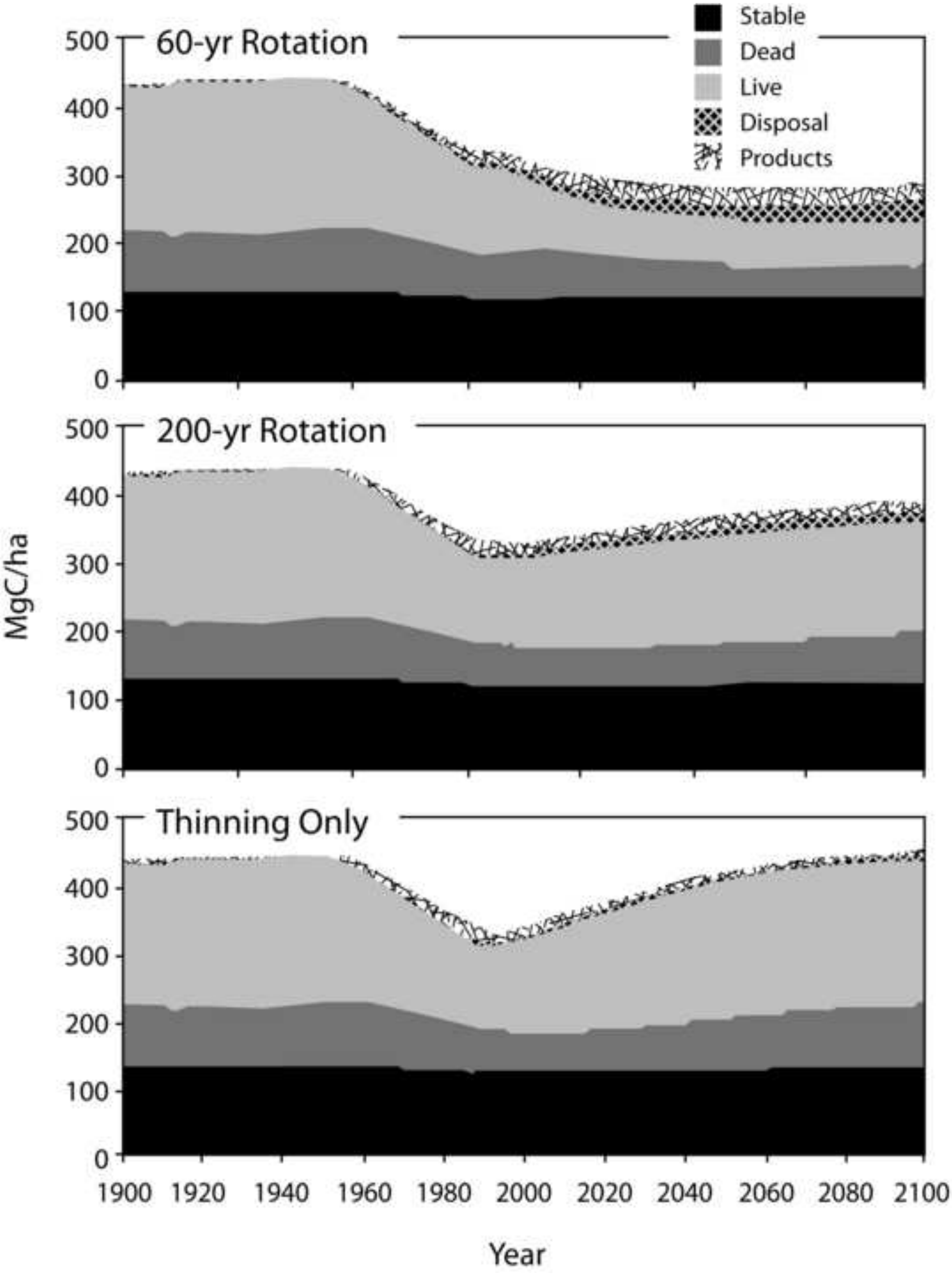

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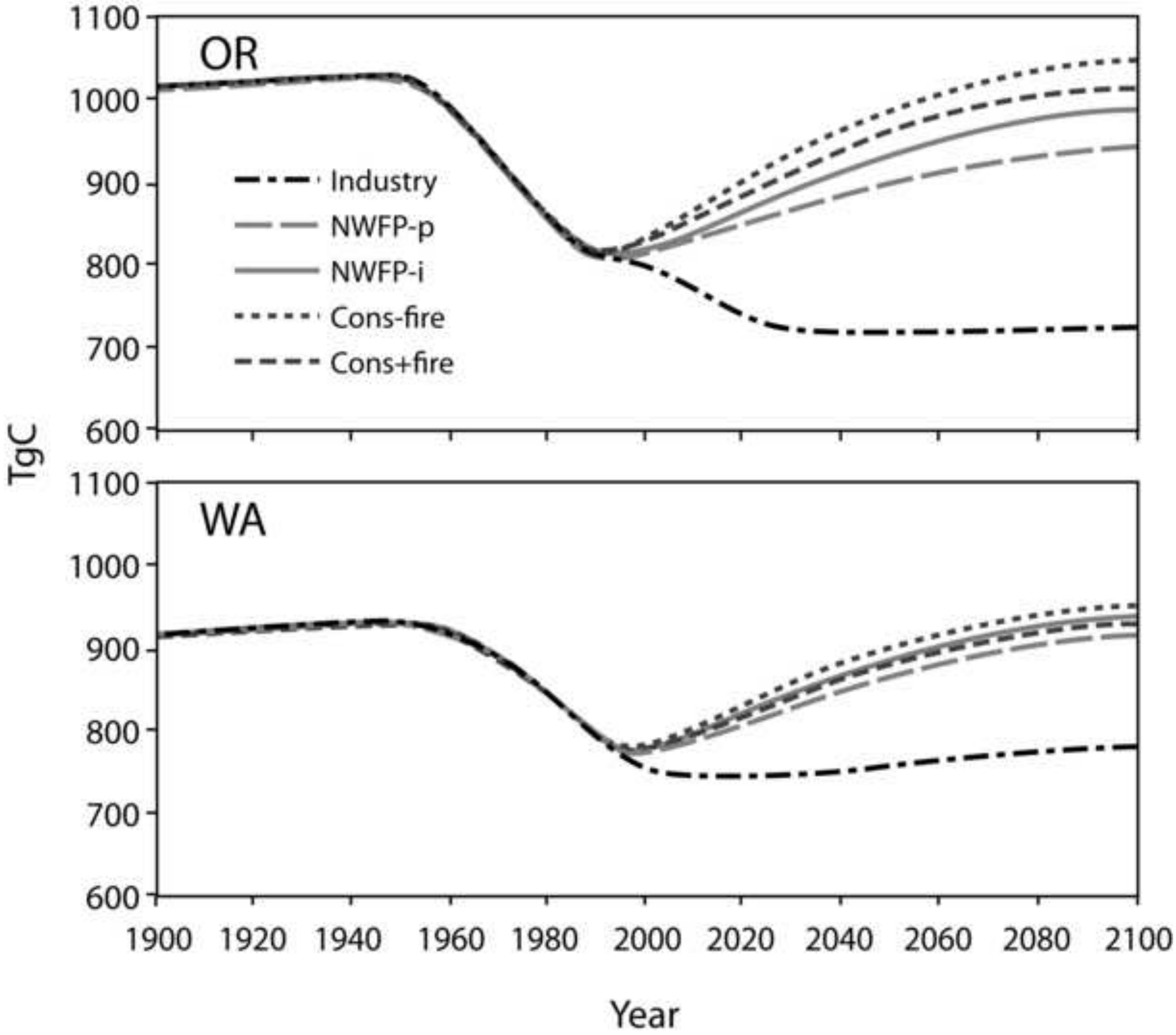
OR
WA
TgC
1100
1000
900
800
700
600
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Year
Industry
NWFP-p
NWFP-i
Cons-fire
Cons+fire

Figure8

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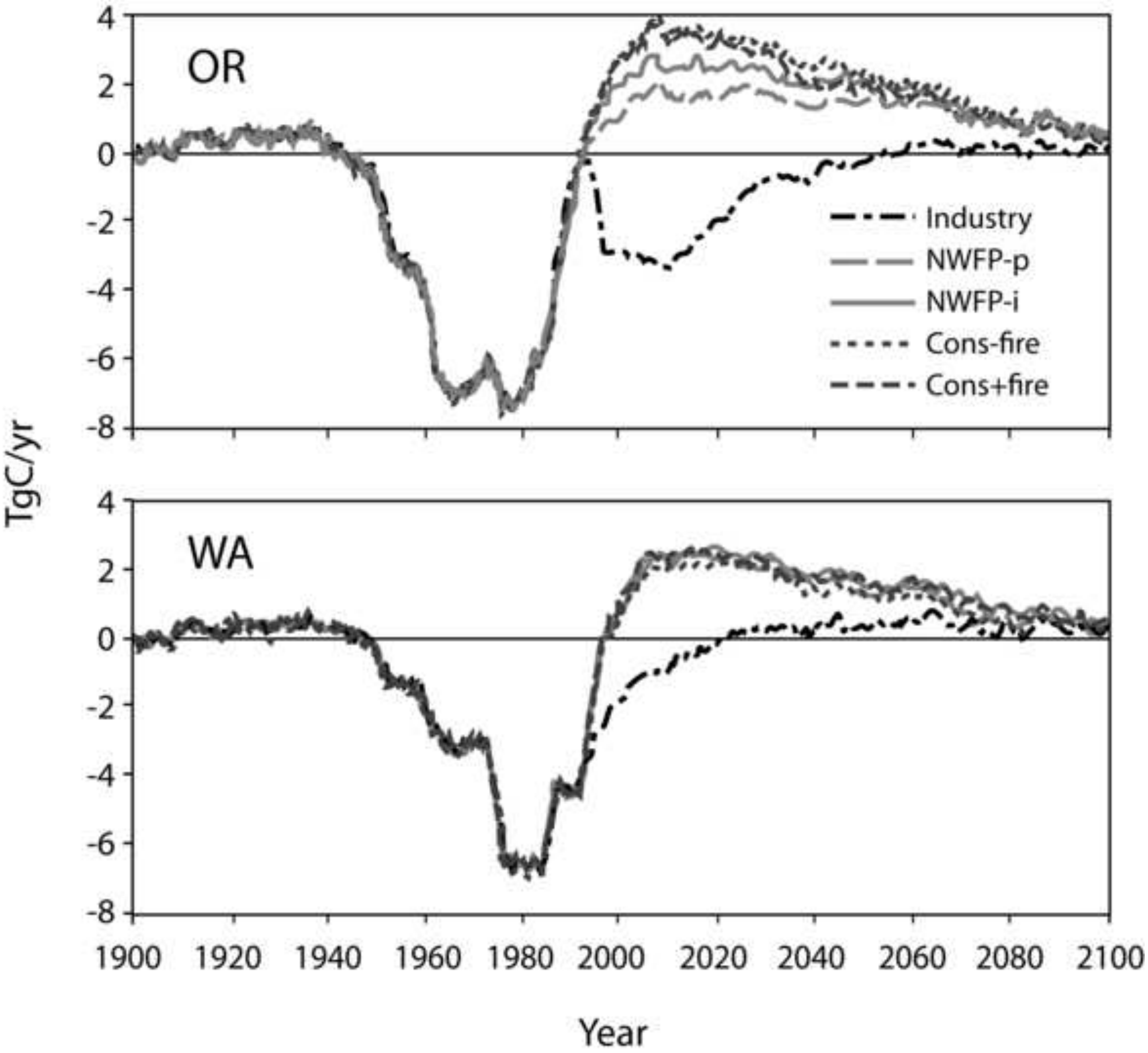

Figure9

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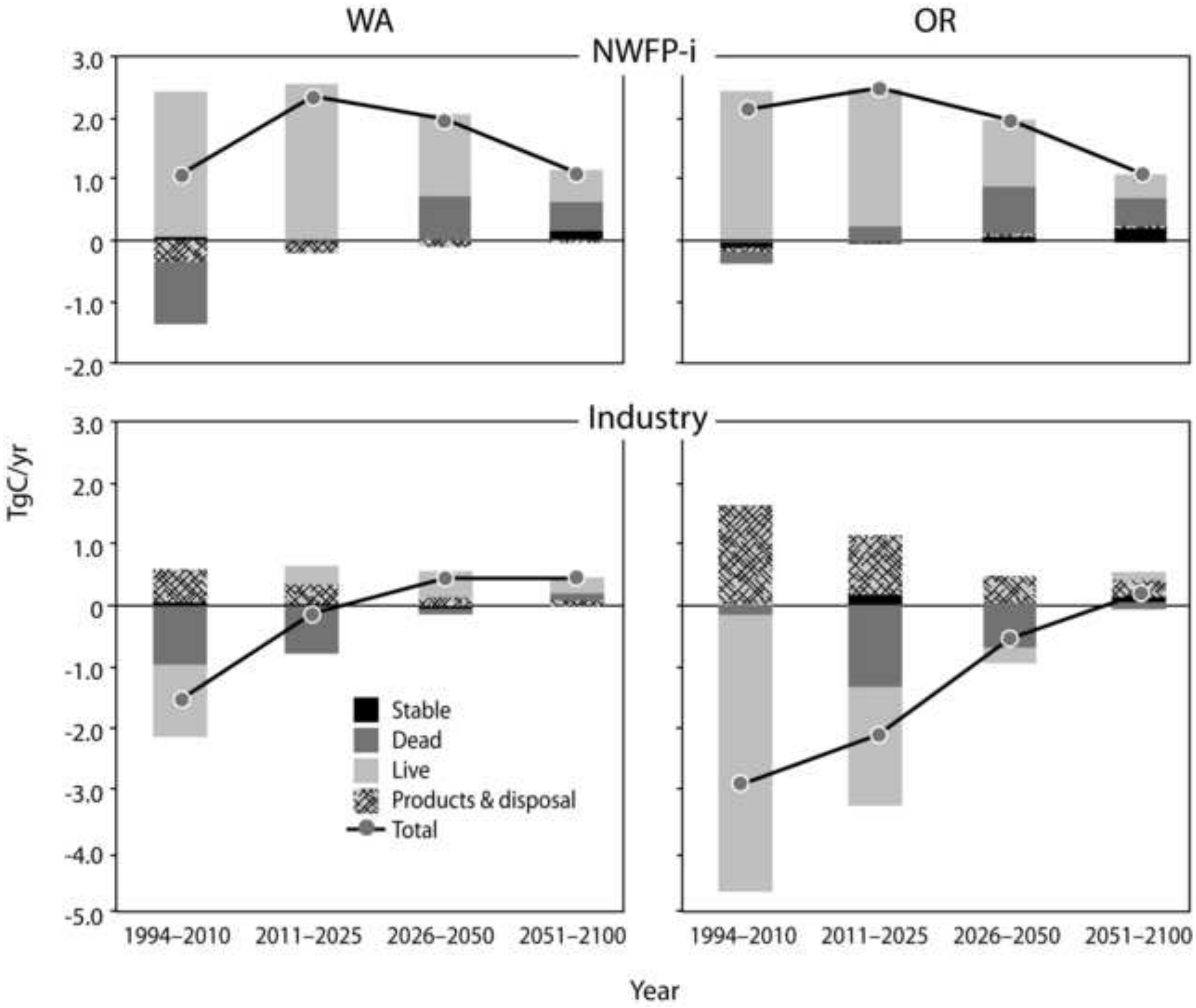

Figure10

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