THE ROLE OF OLD FORESTS AND BIG TREES IN FOREST CARBON SEQUESTRATION IN THE PACIFIC NORTHWEST

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Abstract—Forest ecosystems are an important component of the global carbon (C) cycle. Recent research has indicated that large trees in general, and old-growth forests in particular, sequester substantial amounts of C annually. C sequestration rates are thought to peak and decline with stand age but the timing and controls are not well-understood. The objectives of this study were to determine how the balance of tree growth, mortality, and dead wood decay vary by plant community type, site productivity, and stand age. We compiled remeasured tree and dead wood estimates from 8,767 inventory plots on Pacific Northwest Region National Forest lands and assessed changes by climax plant association zones (PAZs) and site productivity estimates of mean annual increment at culmination (MAI). Estimated maximum C density for old-growth stands (≥300 years old) varied significantly by MAI class within PAZ, but on average stands accumulated 66% of maximum stores by age 100. We did not see a decline in live tree production in older stands in moderate and low MAI classes, but a 33% reduction in high MAI classes. We found that mortality in undisturbed stands increased with stand age such that the net growth in live tree biomass, and the change in total C, was not significantly different from zero in stands over age 400 (0.15 ± 0.64 Mg/ha/yr for total C, 95% confidence interval). Mortality of large trees (>100 cm diameter) exceeded growth, but trees were growing into the larger size classes at a high-enough rate that a net increase in large tree C was seen across the region. Even though large trees accumulated C at a faster rate than small trees on an individual basis, their contribution to C sequestration was smaller on an area basis, and their importance relative to small trees declined in older stands compared to younger stands.

Forest ecosystems play a major role in the global carbon cycle because they can attain high levels of carbon storage, and can gain or lose carbon relatively rapidly (McKinley et al. 2011). Understanding the magnitude and drivers of C flux between forests and the atmosphere has been a focus of research given concerns about the effects of rising levels of atmospheric carbon dioxide on climate change (IPCC Core Writing Team 2007). The rate at which different forests store and release C through growth and decomposition is determined by available resources, environmental conditions, and their seasonal distribution. Some of this variation is reflected in the species composition of the plant community.

The net rate of C sequestration also changes with forest age and successional stage. During forest development after disturbance, after an initial period of loss from decomposition, the net rate at which C accumulates in forest stands tends to peak early in stand development, and then declines as stands age. The timing of the loss phase, peak, and the relative speed of the decline are related to the balance between gross growth, or creation of new organic material, and mortality of living material (with the difference referred to as "net growth").

Old-growth forests store large amounts of C per unit area, but change in their stocks is sensitive to the balance of tree growth and mortality. Recent studies suggests that substantial rates of positive growth in old-growth forests may be more common than previously thought (Luyssaert et al. 2008). The characteristic rates and net effects of gross growth and

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mortality of different tree sizes for C accumulation as stands age are not clear.

The objectives of this study were to assess the role of stand age, plant community type, and productivity on forest C stocks (excluding C in mineral soil) and their net changes as well as net sequestration rates over a diverse range of forest conditions. We conducted the study with inventory data from a systematic sample of National Forests in the Pacific Northwest, USA, with repeat measurements of most aboveground C pools.

METHODS

We assessed C stocks and their change on the 22.5 million ac of forested federal land administered by the Pacific Northwest (PNW) Region of the National Forest System (NFS). These lands are found primarily in the states of Oregon and Washington as well as parts of California and Idaho, U.S.A. NFS lands in this region occur in a great variety of conditions. We grouped individual plots into ten Plant Association Zones (PAZ; Table 1) designated by the climax tree species as classified by field crews using local NFS guides (Hall 1998). The data and compilation methods we used for this study are similar to those used in Gray and Whittier (2014).

There were 8,767 grid points ("plots") within NFS lands that had forested conditions measured 3 or more years apart. We grouped points of the same land class and measurement status on a plot into condition classes and assigned values for stand age, site index, and forest type based on the subsequent compilation of the FIA sample of the same plot location. We

Table 1—Area and environmental characteristics of forested plots on Pacific Northwest national forests by climax Plant Association Zones (PAZ) . Values are means. Listed most common species make up ≥80% of the live tree carbon in a PAZ. PAZs are sorted from lowest estimated mean carbon density (Mg/ha) to highest.

Plant Association Zone (PAZ)	Code	Area (1000 ha)	Annual Precipitation (cm)	Annual temperature (C)	Most common species (ranked)*
Juniperus occidentalis	JUOC	97	48	6.7	JUOC, PIPO
Pinus ponderosa	PIPO	1,102	61	6.1	PIPO
Pinus contorta	PICO	416	84	4.8	PICO, PIPO, LAOC
Pseudotsuga menziesii	PSME	1,212	82	6.1	PSME, PIPO
Abies lasiocarpa	ABLA	776	105	2.2	PSME, ABLA, PIEN, PICO
Abies concolor & *A. grandis*	ABCOGR	1,669	91	5.3	PSME, ABCOGR, PIPO
Tsuga mertensiana & subalpine parkland	TSMEpark	924	183	3.6	TSME, ABAM, ABMAS, ABLA, PSME
Lithocarpus densiflorus	LIDE3	229	210	9.8	PSME, LIDE3, ARME
Tsuga heterophylla & *Picea sitchensis*	TSHEPISI	1,742	188	7.8	PSME, TSHE
Abies amabilis	ABAM	910	222	5.4	ABAM, TSHE, PSME

* In addition to the species names and codes shown in the first two columns, LAOC = *Larix occidentalis*, PIEN = *Picea engelmanii*, ABMAS = *Abies magnifica* var. *shastensis*, ARME = *Arbutus menziesii*

grouped FIA site class codes into three "MAI classes" (<50, 50-120, >120 ft³/ac/yr). Estimates of above- and below-ground live tree and standing dead tree woody C used the regional equations of merchantable bole volume, national FIA equations of stump and bark volume, species-specific wood- and bark-density parameters, and ratios of top and branch biomass to merchantable bole biomass documented in Woodall et al. (2011).

Statistical estimates used standard double-sampling for post-stratification (Scott et al. 2005), with strata defined by national forest boundaries, Wilderness boundaries, and classified Landsat satellite imagery (Dunham et al. 2002). However, a model was used to estimate maximum C density from stand age for each PAZ*MAI class group using a cumulative two-parameter Weibull model:

$$allCdens = exp(a0 + a1*(stdage**a2))$$

where allCdens was total C density (Mg/ha) and stdage was stand age (yrs). Modeling was done using proc NLIN in SAS and datasets were restricted to stand age 300 (150 for the PICO PAZs) to avoid problems with extrapolation of models into regions of sparse data.

RESULTS & DISCUSSION

The maximum mean "total" C density (live and dead woody pools, tree foliage, understory vegetation, and forest floor combined) and the apparent rate at which it was reached varied by plant association zone (PAZ) and productivity (MAI) class. The Weibull model results identified significant differences in the maximum C density attainable by PAZ*MAI class (Table 2). Maximum C density was greater in more productive MAI classes than in less productive MAI classes within most of the PAZs, and also differed among PAZs. The apparent rate of C accumulation (i.e., the steepness of the curve) also differed among PAZs, with TSMEpark and ABCOGR showing the oldest stand age to attain 75% of maximum total C, and PIPO and JUOC the youngest. The mean stand age required to reach the 75% level across PAZs was 125 years.

Sequestration rates varied significantly with stand age and MAI class. Gross growth increased to a plateau at the 80-100 year age class on low MAI sites, rose more quickly to plateau in the 20-40 year class on medium MAI sites, and peaked in the 20-60 year ages and fell by ~33% in older stands on high MAI sites (Fig. 1). Mortality rates for the medium and high MAI classes increased slowly but steadily as stand age increased, eventually matching the rates for gross growth. Consequently, net growth was not significantly different from zero for stands over 250 years old for these two groups. For the low MAI class group, the effect of the rate of C change due to mortality was more variable, with net growth not significantly different from zero for most stand age classes over 175 years old.

Table 2—Predicted maximum total carbon density at stand age 300 (150 for PICO) by plant association zone (PAZ; see Table 1) and MAI class (and 95% confidence intervals). All major pools were included except mineral soil.

	MAI class (m3/ha/yr)		
PAZ	Low (<3.5)	Medium (3.5-8.4)	High (>8.4)
JUOC	26 (9)	—	—
PIPO	77 (5)	100 (12)	66 (27)
PICO	88 (6)	124 (14)	—
PSME	123 (13)	237 (23)	221 (69)
ABLA	149 (17)	187 (16)	201 (81)
ABCOGR	162 (16)	246 (16)	382 (50)
TSMEpark	219 (23)	307 (35)	348 (55)
LIDE3	206 (80)	289 (44)	382 (65)
TSHEPISI	232 (44)	376 (24)	457 (24)
ABAM	271 (43)	381 (29)	425 (33)

Most of the accumulation of C in undisturbed stands across the study region was in small trees, with trees <20 in DBH at time 1 accounting for 69% of the gross growth and 87% of the net growth. Growth of the largest-diameter trees was offset by mortality, with net growth significantly <0 for trees 40-60 in DBH at time 1 (Z=3.86, P<0.001), and not different from zero for

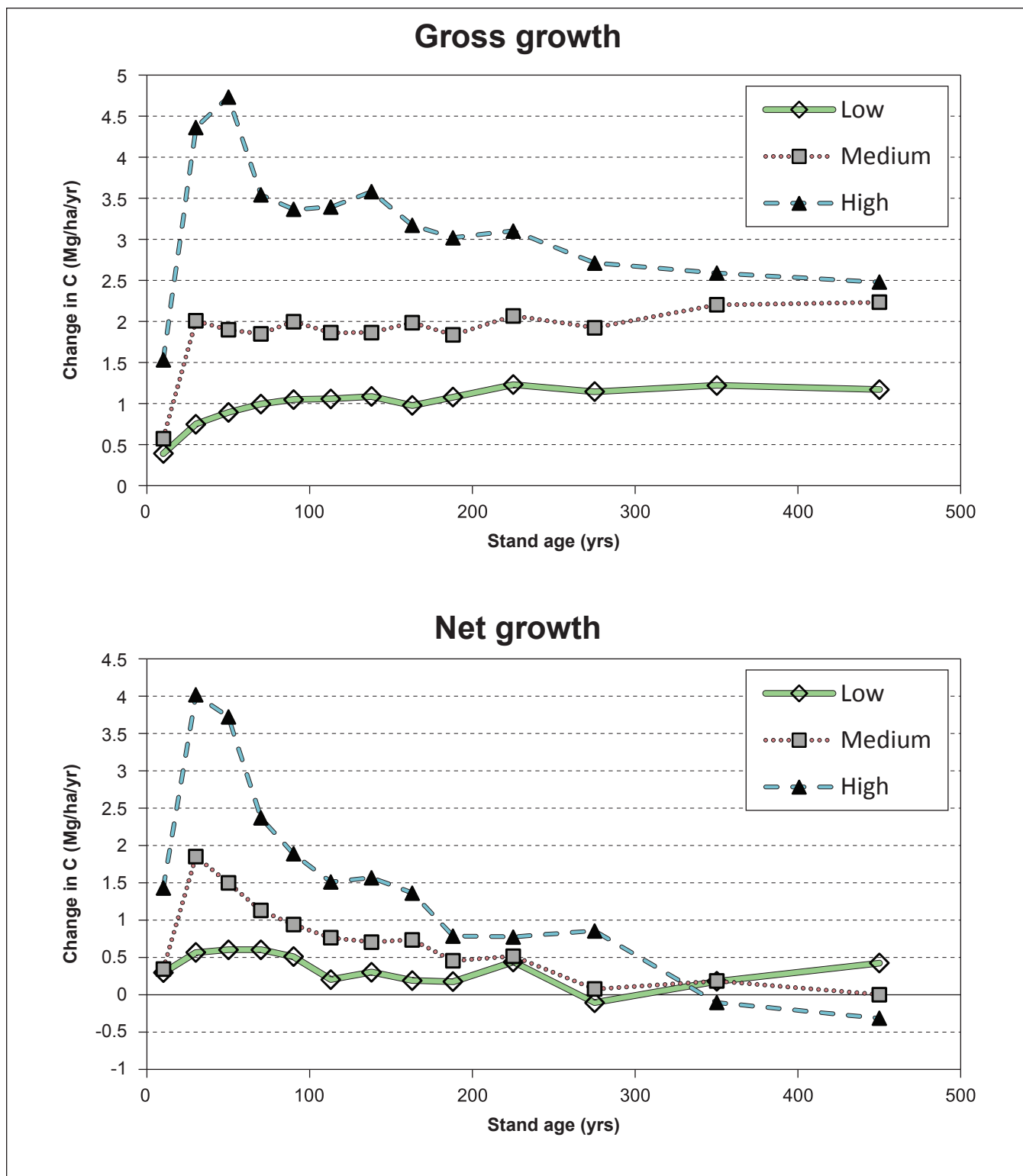## Gross growth

Net growth

Figure 1—Annual changes in carbon in undisturbed stands by MAI class and stand age., showing gross growth on the top, and net growth (growth - mortality) on the bottom.

trees >60 in DBH (Fig. 2). Nevertheless, the density of C in large trees (and all trees >10 in DBH) increased overall in undisturbed stands due to recruitment from smaller size classes ($P<0.05$). The increase in C density in large trees also held true when disturbed stands were included ($P<0.05$), although increases for all sizes were proportionately lower, particularly in the smaller tree sizes.
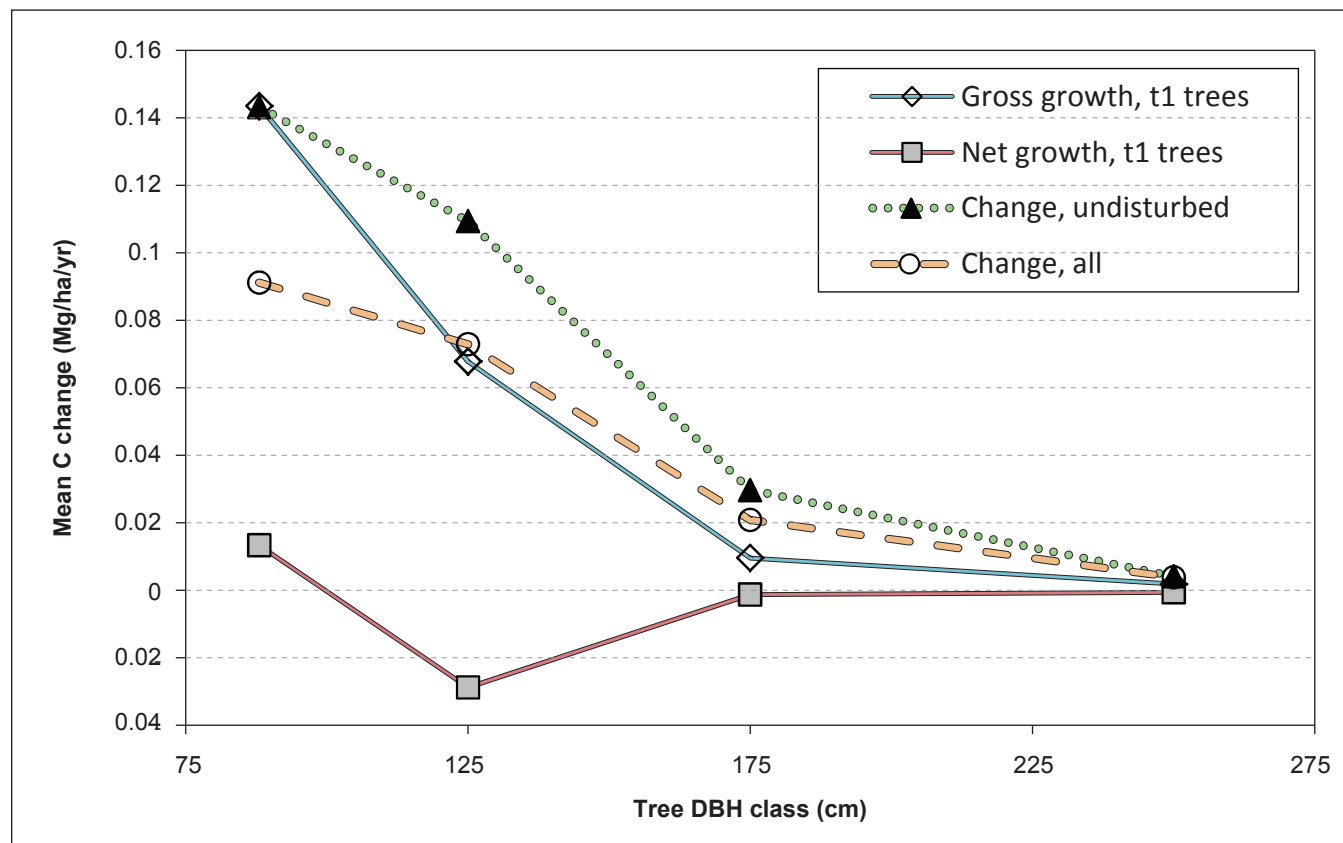
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Figure 2—Change in mean live tree carbon by tree size class, showing gross growth and net growth (growth - mortality) of trees in the class at time 1, and net change (growth into and out of a class plus net growth) for undisturbed stands and for all stands.

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