MARKET TRENDS

4TH QUARTER, 2023

The latest market trends and indices impacting the Timber and Wood Products sectors.

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Q4 2023 HIGHLIGHTS

Market Trends

- Builder sentiment and residential spending trend lower (page 5-6)
- Housing Affordability remains under pressure (page 7-8)
- Total Housing Starts down YOY, Single-Family share gains (page 9-10)
- Inventory of Homes for Sale hold steady YOY (page 11-12)
- Wood Product prices slip in Q4 (page 13-14)
- Most log grades drift lower in line with product prices (page 15-16)
- Gross sawmill margins decline, South:PNW spread holds (page 17)
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Deeper Dive

- Indicative CO_2e Conversion Factors for Timber and Wood Products

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- Data Resources for Carbon Concentrations of Individual Tree Species

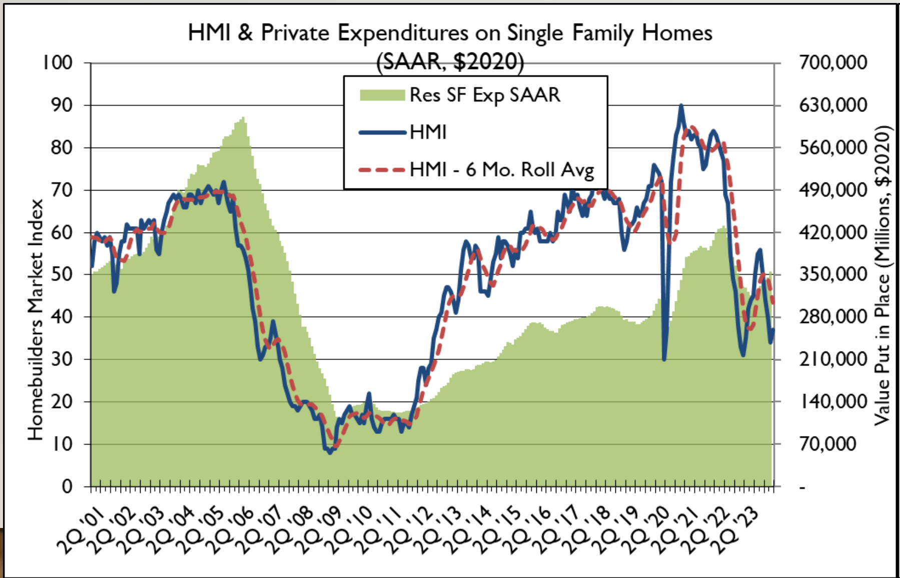
About WillSonn Advisory, LLC

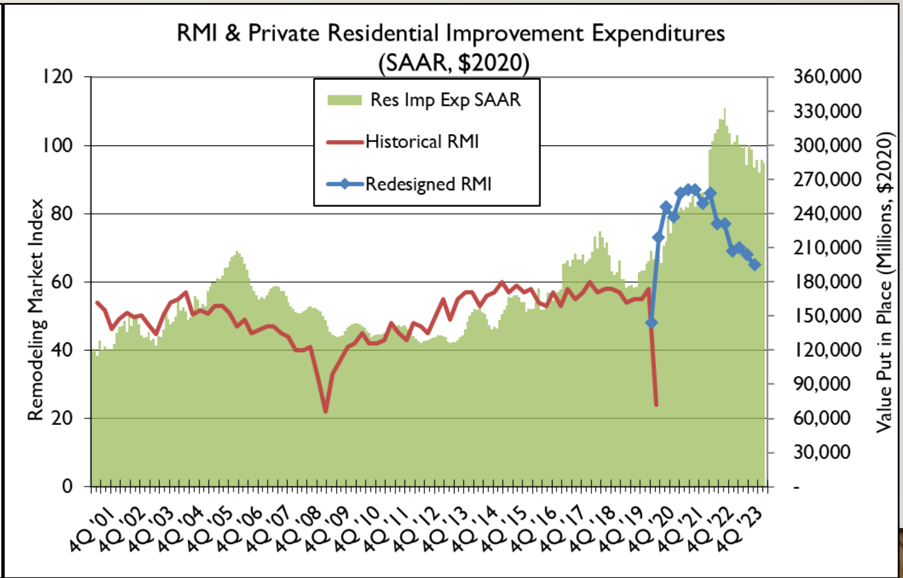
SECTION 1:

LATEST TRENDS

BUILDER SENTIMENT & PRIVATE RESIDENTIAL EXPENDITURES

- **Recent Trends**: The Homebuilder Market Index (HMI) ended Q4 2023 with a reading of 37, 19 points lower than July 2023, though up 6 points from the December 2022 reading. The Remodeling Market Index (RMI) drifted lower to 65 in Q3 2023.
- YTD 2023 Real Expenditures on Single Family New Residential are -15.8% below full-year 2022 expenditure levels, following flat expenditures in 2022. YTD 2023 Real Expenditures on Private Residential Improvement slid -6.9% below 2022 levels, following 2022's 24.3% increase.
- **Explanation**: Homebuilder sentiment moved lower as mortgage rates moved higher. Higher interest rates, declining building material costs and weak housing starts have dampened construction expenditures.
- **Implication**: Improving builder confidence generally bodes well for near to intermediate-term housing starts. Higher mortgage costs risk limiting the pool of qualified buyers and cooling housing turnover. Competition from pre-pandemic consumer interests (e.g., travel, eating out, a.k.a. "revenge spending"), along with elevated borrowing costs may moderate remodeling activity for a few more quarters.
- **Expectation**: Eventually, builder sentiment and construction expenditures should begin to improve when housing recovers, and with it, improving building material prices and stable to declining mortgage rates. However, constrained supply of existing homes for sale, a dearth of developed lots, scarce labor and lower contractor productivity will keep residential expenditures in check in the near-term.

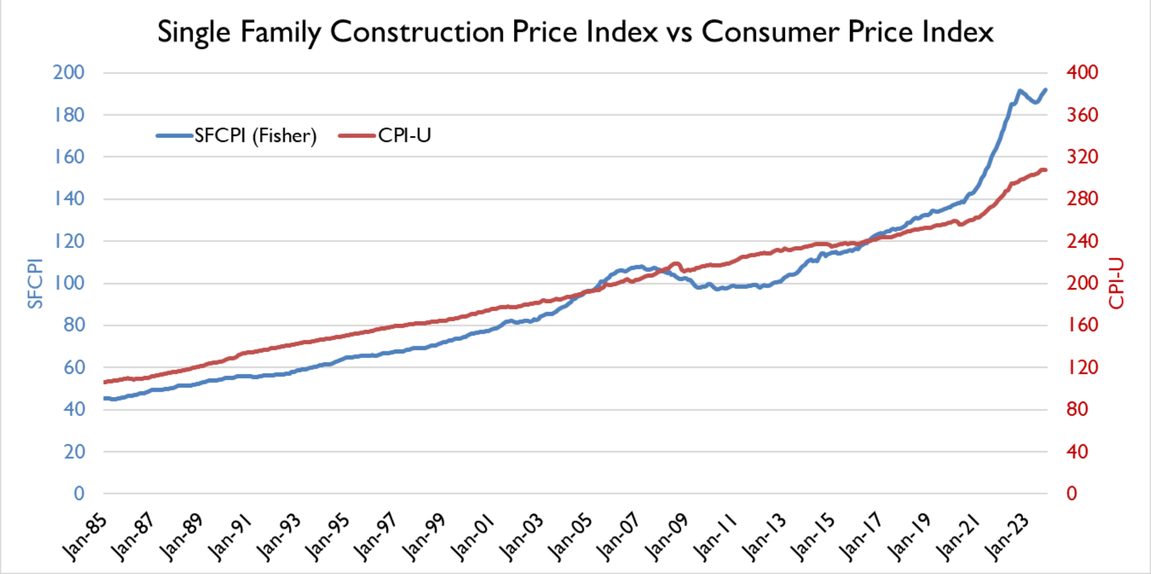




Data Sources: Census Bureau, NAHB, Dept. of Commerce Charts & Analysis: WillSonn Advisory

BEHIND THE NUMBERS: BUILDER SENTIMENT & PRIVATE RESIDENTIAL EXPENDITURES

- **On the previous page**, NAHB's Homebuilder Market Index (HMI) and Remodeling Market Index (RMI) are measures of home builder and remodeling contractor sentiment.
- The monthly HMI and quarterly RMI are dispersion indices, measuring the proportion of respondents who have a positive versus negative view (neutral responses are ignored in the calculation). A reading over 50 indicates a prevailing positive view of conditions.
  - Note that the NAHB instituted a new RMI survey beginning in Q1 2020, such that comparisons to prior years are meaningless.
- Private Construction Expenditures depicted on Single Family Housing and Remodeling are in constant 2020 dollars, (i.e., inflation adjusted) using the Consumer Price Index – All Urban Consumers.
- **In this chart**, I show the Single Family Construction Price Index (SFCPI), produced by the Census Bureau, which reflects the cost of construction, including labor, materials, and permitting, but excludes the cost of land and other non-construction costs. This index also holds the characteristics of homes under construction constant, so it does not reflect cost changes due to increasing or decreasing house size or amenities.
  - Since 2012, it is clearly visible that the Single-Family Construction Price Index has far outpaced overall inflation, at a pace almost 3 times as fast, increasing 89%, compared to 32% for the CPI-U index.

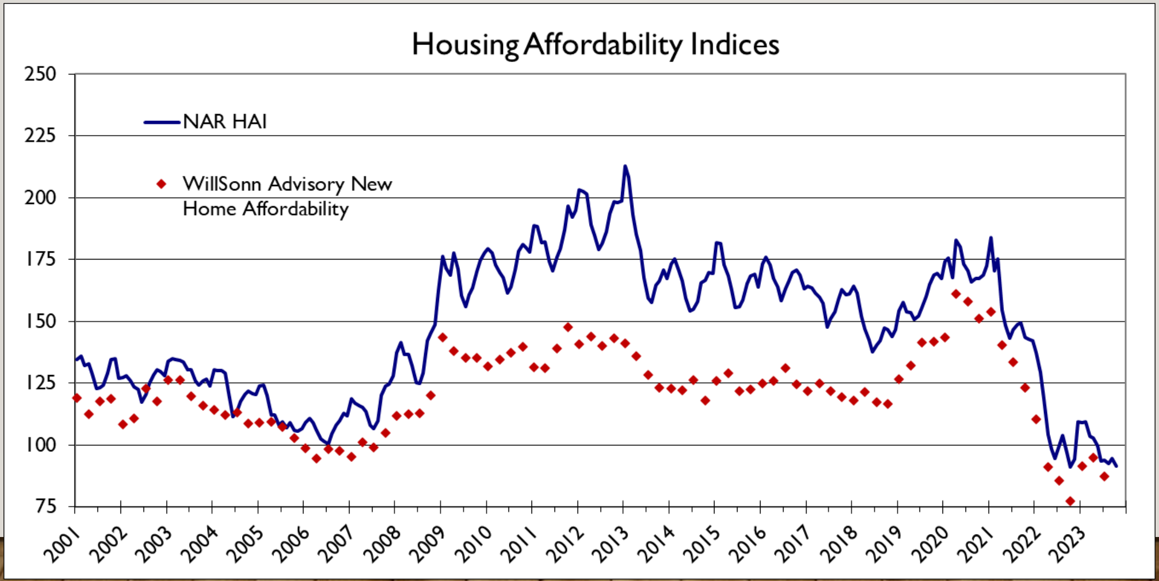


Data Sources: Census Bureau, FRED website

Charts & Analysis: WillSonn Advisory

HOUSING AFFORDABILITY

- **Recent Trends**: The Housing Affordability Index ("HAI") (blue line) remained below 100 in Q4 2023, registering 91 in October. The New Home Affordability (red diamonds) dipped to a reading of 88 in 3Q '23, though still above the record low of Q4 2022.
  - That's six months below 100, a continuous run not seen since the mid-1980's.
- **Explanation**: In 2019 and 2020, mortgage rates eased and median family income accelerated (with the help of federal stimulus payments), bolstering this measure of affordability. Over much of the past three years, home prices continued to march higher in the face of strong demand, while rising mortgage rates and lagging income gains pushed affordability lower.
- **Implication:** Over the years, there is a rather weak link between affordability and housing starts (R-squared of just .17). In fact, the highest levels of housing starts occurred when affordability was in a trough (~2006). Thus, a "fear of missing out" may have spurred some home buyers to buy sooner than later, before home ownership was forever out of reach. Easy credit early 2000's also helped.
- **Expectation**: The efforts to keep a lid on inflation will continue to keep mortgage rates higher while thin existing home inventories will keep home values elevated. Expect affordability to continue to remain under pressure in the coming months, but don't worry too much about its direct impact on housing starts. Also don't expect builders to pass along lower building material costs to buyers as lumber and OSB prices ease; rising labor costs, lot prices and permitting costs are eating away at the added margin.

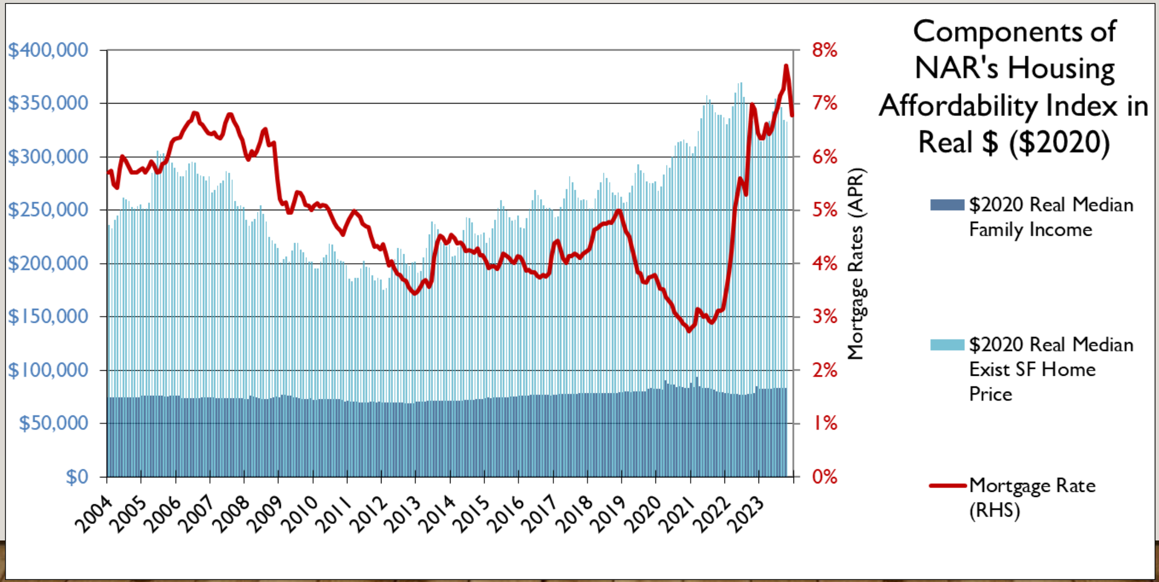


Data Sources: NAR, Census Bureau,, Dept. of Commerce

Charts & Analysis: WillSonn Advisory

BEHIND THE NUMBERS: HOUSING AFFORDABILITY

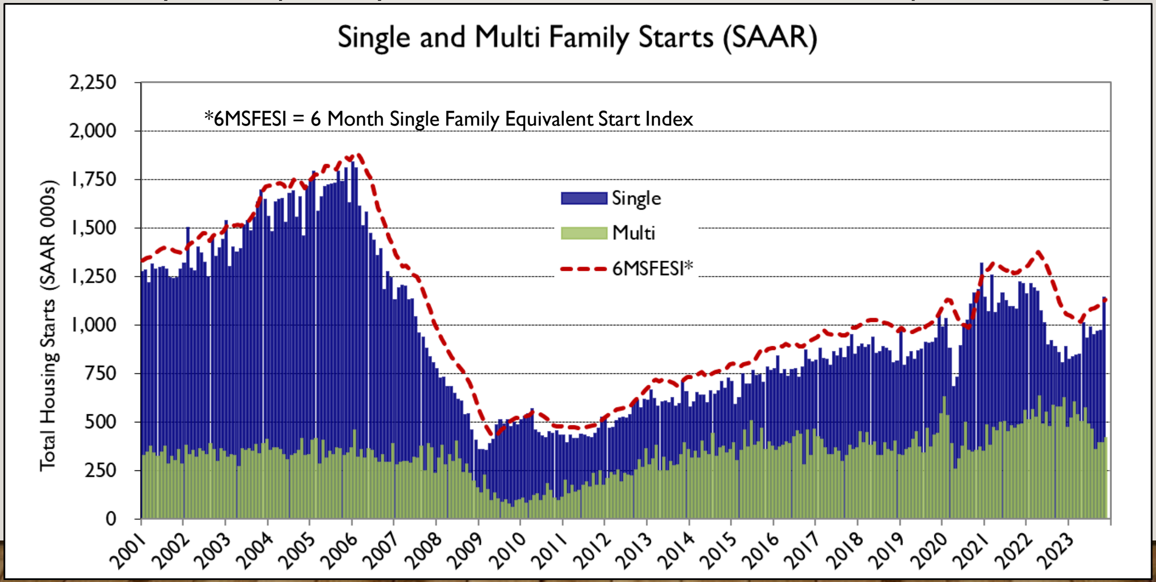
- **On the previous page**, the National Association of Realtors' Housing Affordability Index ("HAI") is based on three inputs: list prices of existing homes for sale, 30-year fixed mortgage rates and median family income. WillSonn Advisory's New Home Affordability uses the actual sales price of new homes, with the same income and mortgage rate figures as the HAI.
  - A reading of 100 means that a family with median income would need to spend fully 25% of its monthly income on a mortgage to purchase the median priced existing home. A reading of 140 means that 25% of the median family income is 1.4 times the mortgage payment for the median priced existing home.
- **The chart below** displays the movement in the three components of the NAR Affordability Index – home prices, mortgage rates and family income – in Real dollar ($2020) terms. Adjusted for inflation, YTD 2023 compared to 2022, median real home prices declined -3.0% while real Median Family Income gained 5.8% (*Note: new Census Bureau estimates of Median Family Income were recently adjusted upward, retroactive to 1/1/2023*). But with average mortgage rates 27% higher, Mortgage Payments for the median priced home were 21% higher than 2022, eating up an increasing proportion of family income. All of this resulted in a declining Affordability Index.
- In October 2023, mortgage rates averaged 7.7%, 72 basis point higher than October 2022. Holding home price and income steady, a 50-basis point increase in mortgage rates drives the Affordability Index down about 10 points. 30-year Fixed Rate Mortgages have retreated since October, averaging 6.8% in December 2023, so expect affordability to move above the 100-level in the near-term.



Data Sources: NAR, FRED website
Charts & Analysis: WillSonn Advisory

HOUSING STARTS

- **Recent Trends:** Through November 2023 Housing Starts registered 1.412 million units, compared to 2022's total of 1.554 million units. Single Family Starts for the year are down -7% while Multi Family Starts were down -13%, compared to 2022. November's preliminary reading of 1.560 million units is still below the recent peak of 1.805 million units registered in April 2022, but certainly improved.
  - The WillSonn Advisory "6 Month Single Family Equivalent Start Index," recasts a multi-family unit into a single-family unit based on relative wood use, so a better measure of Housing Start's demand for wood. November's 1,128,000 unit reading moved higher from its recent low of 1,019,000 in April, now at 60% of the 2006 peak of 1.9 million SFES's.
- **Explanation**: Higher home prices alone were a threat to sustained gains in Housing Starts. Coupled with elevated interest rates, Family Income gains have been more than offset, keeping aspiring homeowners in the rental market and shifting the market from single to multi-family construction (and pushing rents higher).
- **Implication**: Housing Starts typically account for 30%-40% of wood usage, so as housing goes, so goes lumber and panel demand.
- **Expectation**: With a recession looking less likely and/or severe, Housing starts are expected to slowly improve over the next few quarters. In the longer-term, we can expect housing to continue to gain steam as the housing deficit is replenished and as existing home availability remains tight. Gains may be tempered by limits on construction labor and developed lots, and tight lending standards.

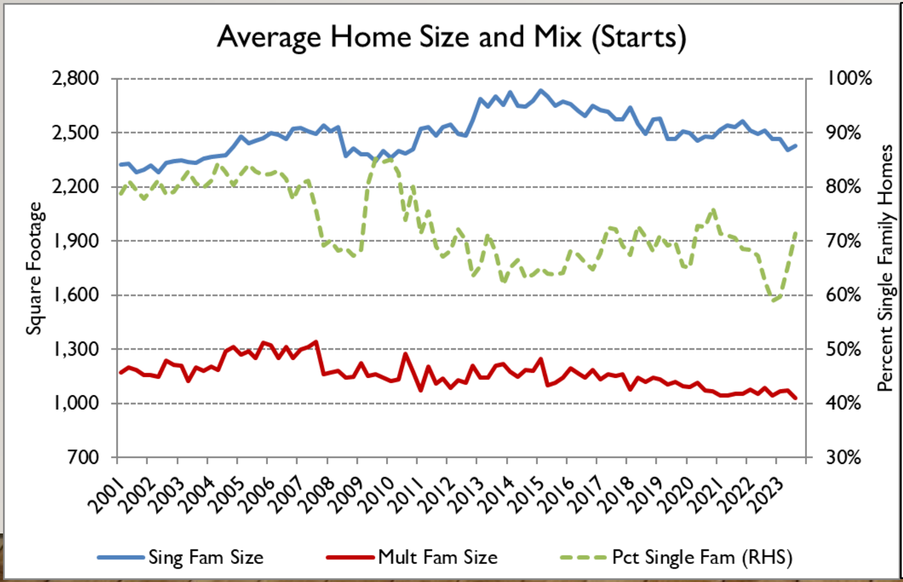


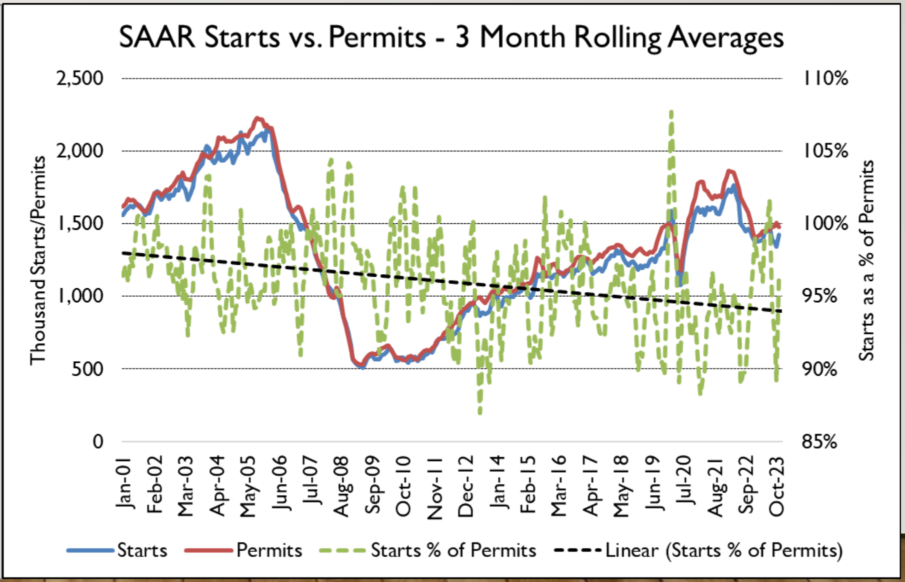
Data Source: U.S. Census Bureau
Charts & Analysis: WillSonn Advisory

BEHIND THE NUMBERS: HOUSING STARTS

- For the **Single-Family Equivalent Start Index** on the previous page, Multi-family units use approximately 2/3 as much wood per square foot of construction compared to a Single-Family Unit, and since Multi-Family Units are about half the size of Single-Family homes, I count them as a 1/3 single-family-equivalent.
- On the **bottom left chart**, you can see that the size of Single-Family Home Starts continue to trend smaller in 2023, averaging just 2,430 sq. ft., -2.8% smaller than 2022's average of 2,500 sq. ft. The average size of Multi-Family Units started in the first three quarters of 2023 averaged 1,059 sq. ft., down slightly from the 2022 average of 1,066 sq. ft. The share of Single Family starts has inched higher to the 66% range through the first three quarters of 2023, on par with 2022 and 17 points below the pre-bust average of 82%.
- The ratio of Starts:Permits has improved in the first eleven months of 2023, averaging 97%, compared to 93% in 2021 and 2022. In the **bottom right chart**, you can see that the ratio had been declining over time, such that the old rule of thumb of ~97 Starts per 100 Permits came into question. Ongoing monitoring is warranted. Tightening builder credit since the housing-led Great Recession of 2008-09, along with volatile building material prices, were likely contributing factors. As housing starts regain momentum, and when (or if) the market shifts towards more single family starts, I expect the ratio to steady itself in the mid to upper-90's range.

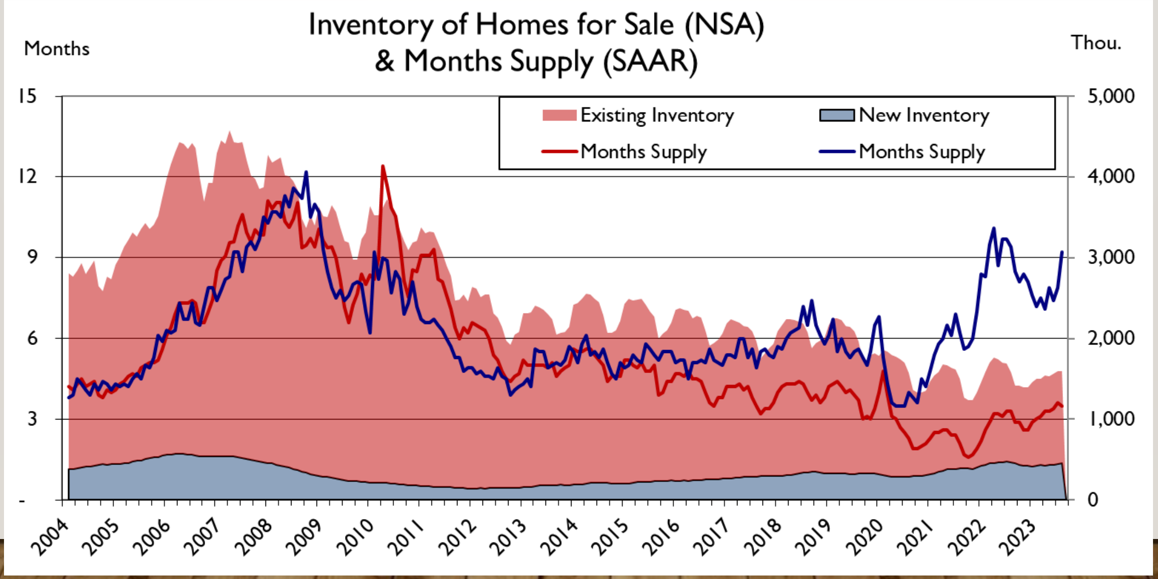
Data Source: U.S. Census Bureau Charts & Analysis: WillSonn Advisory





PACE OF HOME SALES & INVENTORIES

- **Recent Trends**: The Inventory of Homes For Sale (Existing + New) moved higher to 1.590 million units in November, up 175,000 units from December 2022, but even with November 2022. Separately, Existing Home Inventories are up 10k units, while New Home inventories are down 3k units, compared to November 2022. At their respective current pace of sales, there are a scant 3.5 months of sales in Existing Home inventories, and an excessive 9.2 months of sales in New Home inventories. Five or six months is normal.
- **Explanation**: The inventory of existing homes has been suppressed as homeowners have stayed put, increasing tenure from six or seven years a generation ago, to thirteen years today. Elevated mortgage rate and higher home prices are impediments to turnover of existing homes. New home inventories have surpassed the high end of the normal range as poor affordability has pushed buyers to the sidelines.
- **Implication**: Tighter inventories are contributing to higher home prices, which in turn limits existing homeowners' options to purchase replacement homes, a vicious cycle. While New homes are a major user of building materials, many R&R projects occur within the first couple years of ownership, so lower Existing home turnover can have a negative effect from the repair and remodel sector as well.
- **Expectation**: It is unlikely that the US housing starts will return to basement levels of the late 2000's when lax mortgage standards in the early 2000's torpedoed the housing sector. As predicted, with elevated mortgage rates, we are beginning to see lower levels of existing home sales and new home inventories rebuilding, along with a slower pace of home price growth.

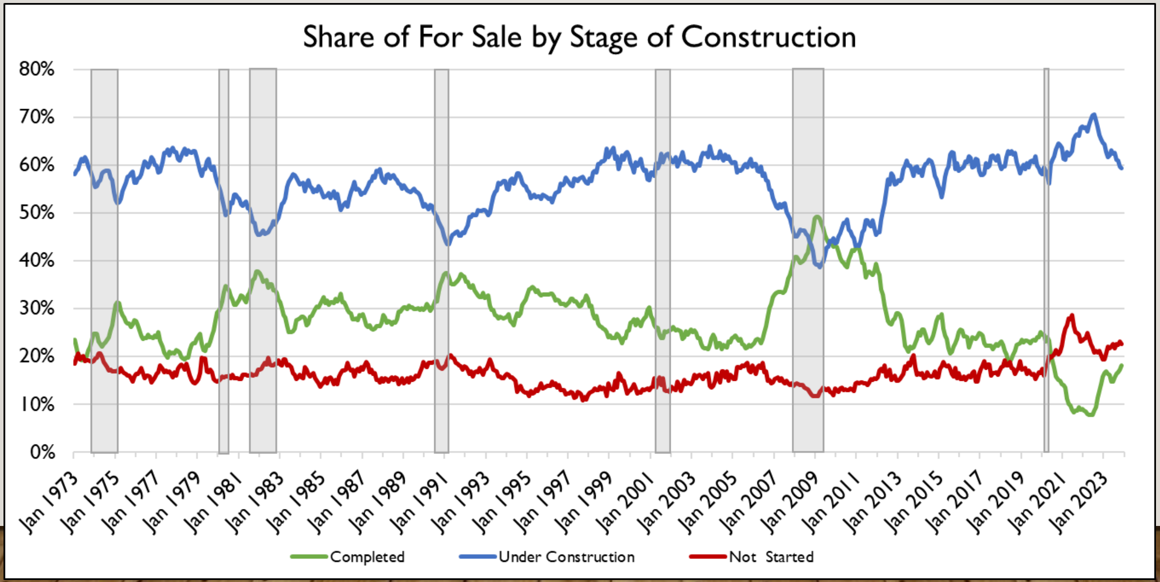


Data Source: U.S. Census Bureau, NAR

Charts & Analysis: WillSonn Advisory

BEHIND THE NUMBERS: PACE OF HOME SALES & INVENTORIES

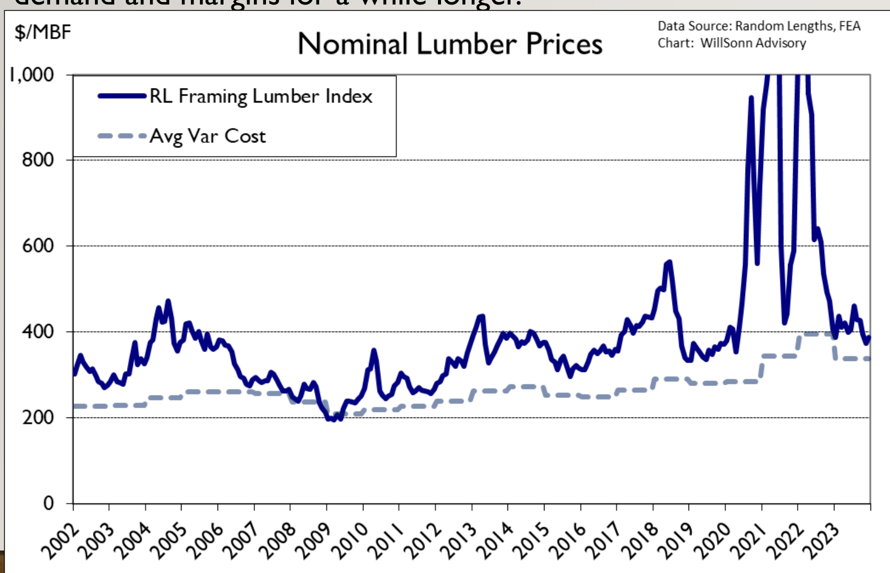
- **On the prior page, t**he inventory of New and Existing homes combines data from the National Association of Realtors ("NAR") which provides data for Existing home sales (both single and multi-family homes), and the U.S. Census Bureau, which provides data for New home sales (single family only). Inventory figures are not seasonally adjusted ("NSA"). Months Supply is derived from inventories and monthly sales volume, which are seasonally adjusted (Seasonally Adjusted Annual Rate, or "SAAR").
- **In the chart below**, I've plotted the share of New Homes for sale, by stage of construction. Also shown on the chart are the US recessions, in grey bars. What I notice in this chart is that a US recession is typically accompanied by a buildup (up to 30%+) in the share of Completed Homes for Sale and the longer the recession, the more pronounced the buildup of Completed Homes becomes. These patterns are typically mirrored by a decline in the share of homes Under Construction (below 50%).
- Of the 460,000 New units for sale at the end of November 2023, only 18% were Completed (well above the recent 47-year low of 8%), 59% were Under Construction, and 23% had Not Yet Started (down from its recent record of 29%, but still elevated). If a typical recession is coming, there is a lot of change needed for the Completed and Under Construction shares.
- With the onset of the pandemic, and its impact on construction activity (slowed) and demand (heightened) we saw the inventory of homes Completed plummet, while the share of homes Not Yet Started climbed. Higher mortgage rates in 2022 and 2023 drove demand for new homes lower, allowing inventory of Completed homes to begin to recover.

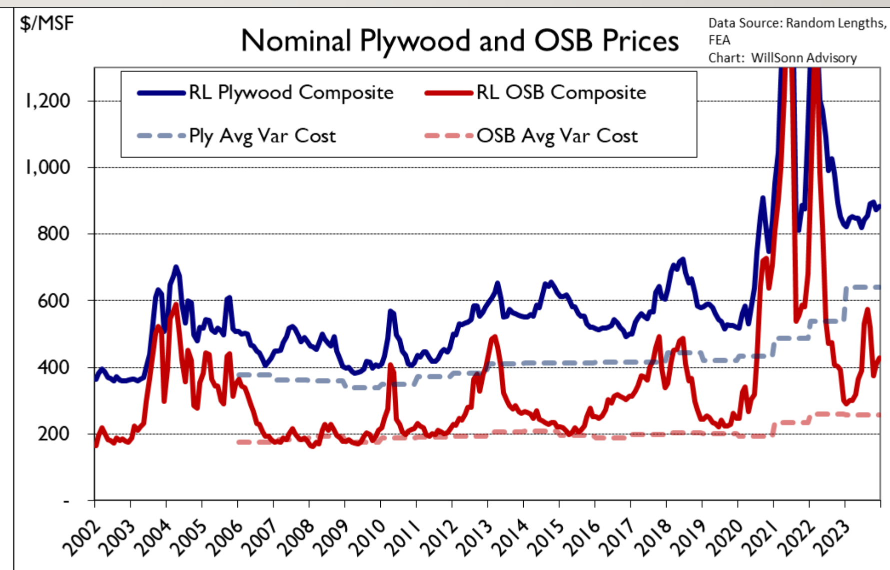


Data Source: U.S. Census Bureau, NAR
Charts & Analysis: WillSonn Advisory

WOOD PRODUCT PRICES

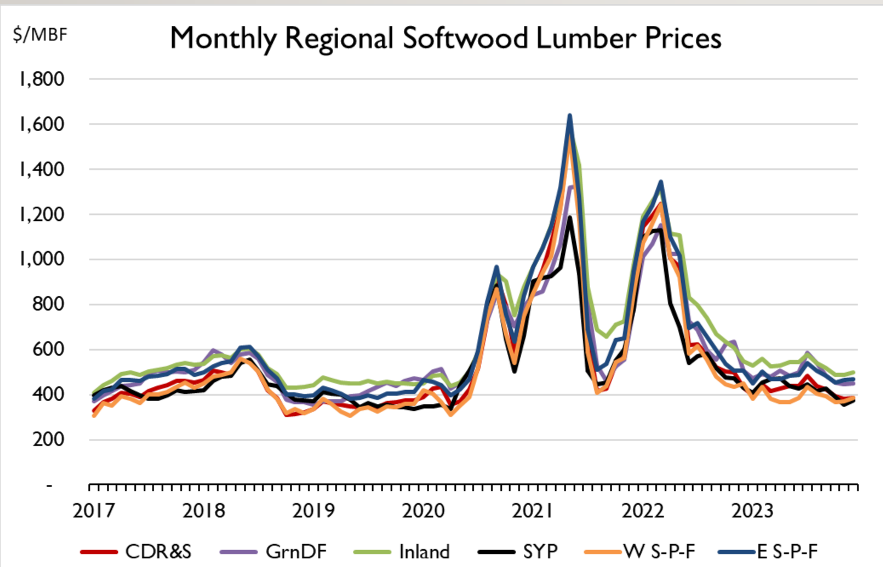
- **Recent Trends**: The Random Length Framing Lumber Composite Index in Q4 2023 lost ground, falling -12% from Q3 and -51% below Full Year 2022 prices. OSB prices reversed course, losing -25% in Q4 from Q3, ending the year down -43% from FY 2022 prices. In contrast, Q4 Plywood pricing ticked up 2% from Q3, finishing the year -20% below FY 2022. Only softwood plywood remains at or above its historical peaks prior to the pandemic.
- **Explanation**: A cooling off of the housing sector has helped bring prices down (and relative price stability) compared to the extreme prices seen during the pandemic when manufacturers, construction and transportation sectors wrestled with periodic labor tightness, rising labor and volatile fuel costs, covid-related work absences and spot capacity closures for multiple quarters. Plywood held up better than OSB due to lower exposure to the housing sector and reduced supply (down -9% since 2019 vs. -2% for OSB).
- **Implication**: As predicted, when building material prices became excessive, some buyers delayed, downsized or abandoned projects, reducing demand and thus price. Normally, high prices would spur additional mill shifts, a surge in imports and substitution from non-wood materials, each of which were muted during the Covid-19 pandemic. Elevated interest rates are now having a ripple effect.
- **Expectation**: As product prices moderate, interest rates stabilize, and supply improves, builder and DIY demand should improve, and with it, product prices. However, labor remains tight (both in the mills and on construction sites) and elevated interest rates will suppress demand and margins for a while longer.

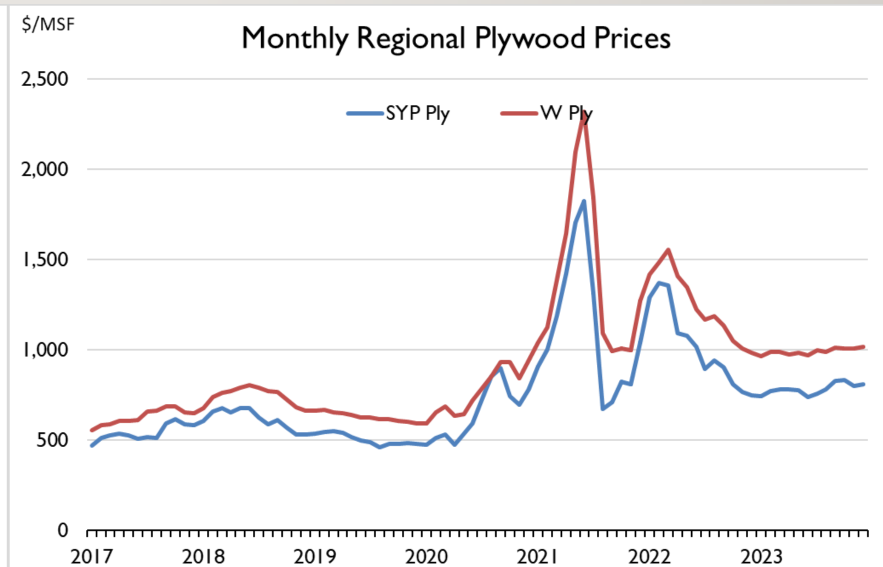




BEHIND THE NUMBERS: WOOD PRODUCT PRICES

- All North American regions saw erosion in product prices during the fourth quarter of 2023.
- Regionally in Q4 2023 relative to Q3 2023
  - West Coast lumber mills saw a -14% drop in Coastal Dry Random & Stud ("CDR&S") prices and -16% Green Douglas-fir prices.
  - Inland sawmills saw prices decline a more modest -10% in Q4.
  - Southern Yellow Pine ("SYP") sawmills saw prices slip -13% in Q4.
  - Canadian components of the Random Lengths Framing Composite Index saw S-P-F prices give back -9% in the West and -10% in the East.
- Fourth quarter plywood prices gained modestly in both regions, in contrast to Lumber and OSB prices. Southern Plywood prices were up 3% while Western Plywood was up 1% in the fourth quarter relative to the third.
  - The Housing sector makes up 50-60% of Plywood consumption, versus 80%+ of OSB consumption.

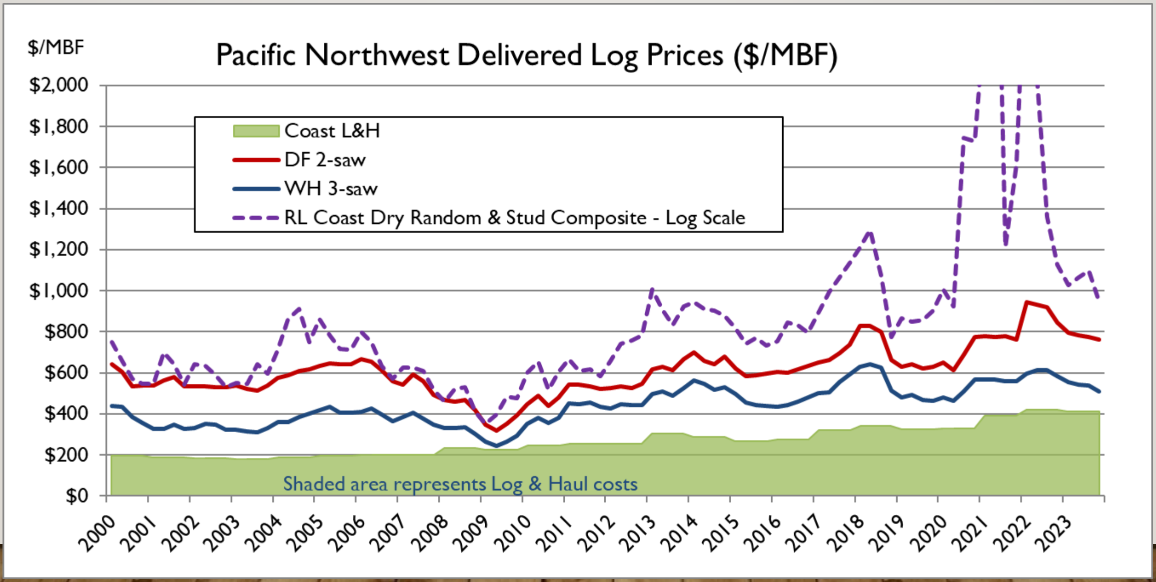




PNW LOG PRICES

- **Recent Trends**: Delivered log prices continued to drift lower in the fourth quarter with Douglas-fir 2saw and western hemlock 3saw log prices were off -1% and -6%, respectively (both -16% below 2022 levels). Over the past 10 years, 4th quarter DF and WW log prices have typically been flat, so this quarter's movement fell short.
- After adjustments for changes in lumber recovery, the Random Lengths Coast Dry Random & Stud Composite price (on a log scale) retreated -$149/MBF (-14%) during the third quarter.
- **Explanation**: With lower demand from housing and the R&R markets, western mill output has declined, and with it, log consumption. Losses due to fire in PNW were lower than recent years. Weaker lumber prices and more normal logging conditions are now undercutting log sellers' pricing power, though log prices remain elevated.
- **Implication**: As a result, mills were able to exert downward pressure on log prices through 2023.
- **Expectation**: Over the past 10 years, first quarter DF 2saw log prices usually move up $22/MBF while WH 3saw typically see prices gain $7/MBF. With seven quarters of moderating lumber prices behind us, home construction still underperforming, and a relatively mild fire season in 2023, delivered western log price are expected to remain under pressure until fundamentals change.

Historically, with about a one-quarter lag, western lumber prices have been the primary driver in West Coast domestic log pricing, though changes in supply and export log prices do exert some influence.

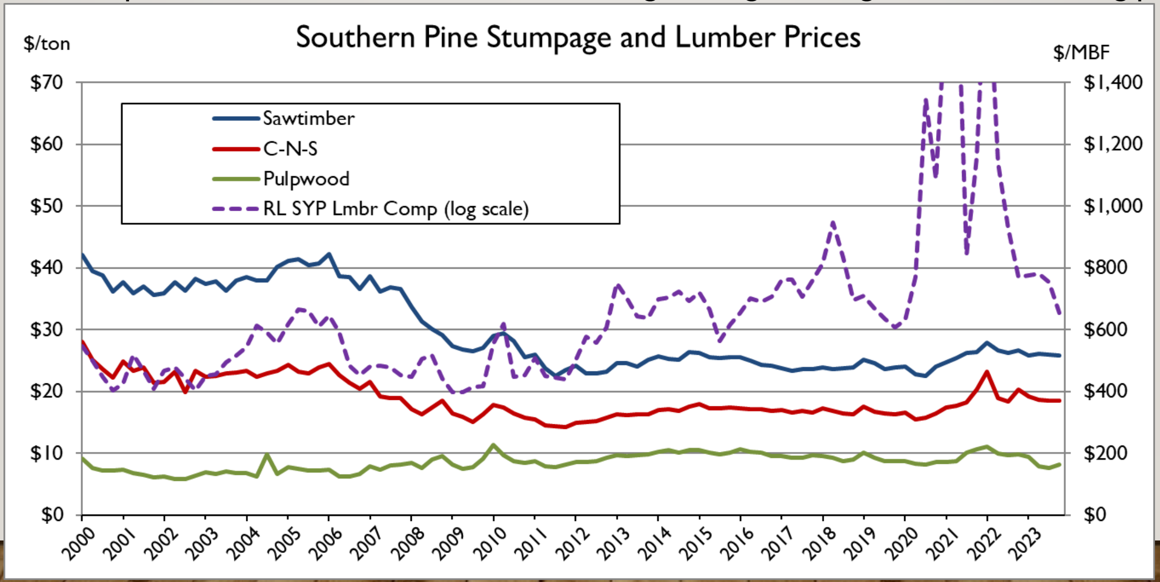


Data Source: Oregon DOF, WA DNR, Random Lengths, FEA, Log Lines

Charts & Analysis: WillSonn Advisory

SOUTHERN PINE LOG PRICES

- **Recent Trends:** Southern Yellow Pine Sawtimber prices edged lower \$0.19/ton in Q4 (<1%), Chip-n-saw stumpage prices ticked up \$0.09/ton (<1%) and pine pulpwood recovered \$0.55/ton (7%). Relative to full year 2022, fourth-quarter 2023 PST was down -4%, CNS was down -8%, and PPW is off -20%.
- The Random Lengths SYP Lumber Composite, adjusted for lumber mill recovery, drifted lower, losing \$98/MBF, or -13% in Q4 '23 compared to Q3 '23, now registering -44% below full year 2022's prices.
- **Explanation**: SYP Stumpage prices typically move higher as Fall logging conditions restrict logging access. The big story in 2023 has been the dramatic drop in pulpwood prices, as mounting pulp mill closures, growing sawmill residual output and declining market pulp prices converged to undercut pulpwood prices. Despite growth in southern lumber capacity, sawlogs remain plentiful in the region.
- **Implication**: Sawtimber to Pulpwood price ratios were 3.2:1 in Q4, close to its highest ratio since 2009, though still weak. Ratios below 4:1 undercut landowner incentives to grow sawtimber.
- **Expectation**: Q1 markets typically see prices move higher, \$0.20 to \$0.60 per ton, as Winter rains limit logging access. Even though 2022 Sawlog prices hit a 12-year high (and CNS a 15-year high), my longer-term view has not changed; SYP sawtimber prices will remain under pressure for an extended period as plentiful inventory on the stump, modest gains in housing starts, increased plantation productivity, and incremental improvements in mill recoveries all work against significant gains in southern log prices.



Data Source: Timber Mart South, Random Lengths, FEA

Charts & Analysis: WillSonn Advisory

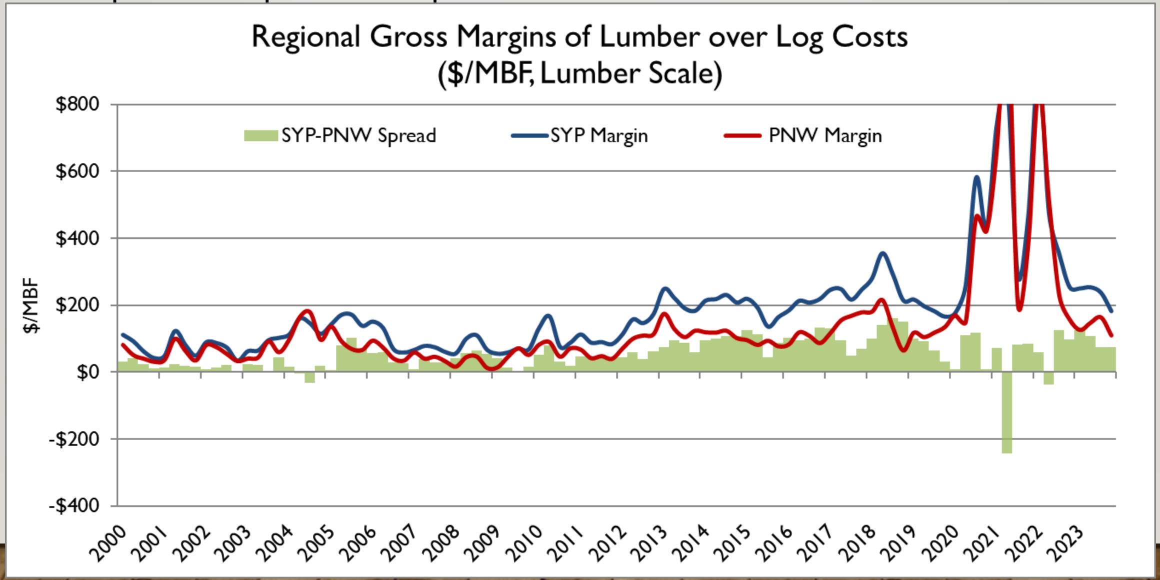
REGIONAL GROSS MARGINS

Sawmill Gross Margins (lumber price minus delivered raw material costs) in the Northwest and South were derived from the figures on the previous two pages. The difference in margins between the two regions is the “spread.”

- **Recent Trend:** The gross margin spread between Southern and PNW sawmills remained at new-normal levels in Q4 at $74/MBF in favor of the South, down a hair from $75/MBF in Q3. The $74/MBF spread compares to an average spread in 2022 of $62MBF enjoyed by southern mills. Margins in volatile 2021 were at parity (on average). Gross margins in the PNW contracted this quarter, from $164/MBF to $110/MBF in the PNW, and in the South, from $239/MBF to $184/MBF. Over the past 10 years, Southern sawmills have enjoyed gross margins over $200/MBF more than 75% of the time, while PNW mill gross margins hit that mark just 25% of the time.
- **Explanation**: Since 2012, log export markets and declining Interior BC lumber production pushed PNW log prices to historical highs. In the South, persistent excess inventories of mature sawtimber on the stump have kept downward pressure on sawtimber prices, even as lumber prices improved. Both regions saw gross margins balloon (twice!) during the pandemic-fueled run-ups in lumber prices.
- **Implication**: Manufacturing capital investments will continue to favor the US South as its margin advantage persists.
- **Expectation**: I expect the spread between the PNW and South to settle in the $50-100/MBF range as lumber markets stabilize, in favor of the South. These spreads will persist until standing sawtimber inventories are worked down in the South over the next several years, or until expanded SYP lumber production pulls lumber prices down.

Data Sources: Timber-Mart South, Random Lengths, FEA, Oregon DOF, WA DNR

Chart & Analysis: WillSonn Advisory

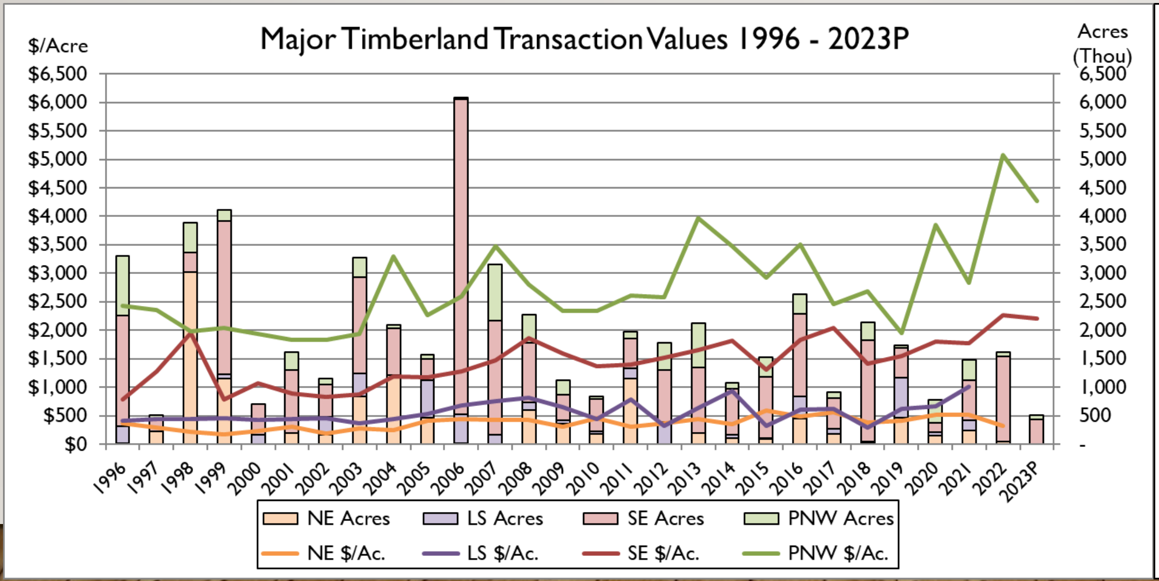


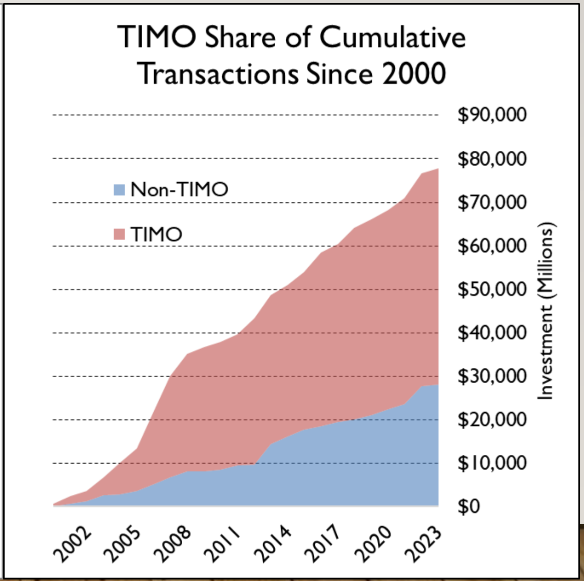
Assumptions: 67/33 weight of DF2saw and WH3saw in the PNW, and a 75/25 weight for S/T and CNS in the South (using 7.5 tons/MBF, along with FEA's estimates of Cut & Haul cost for S/T and CNS). All figures are lumber scale, and regional differences in lumber recovery factors are incorporated.

REGIONAL TIMBERLAND TRANSACTION VALUES

- **Recent Trends**: Preliminary 2023 timberland sales totaled $1.28 billion on 509,000 acres, with another +/- 160,000 acres sold at undisclosed values. All but three sales have been in the US South. In 2022, 3.4 million acres sold for a total of $5.7 billion – we are at ~20% of 2022's pace through eleven+ months of 2023.
- By investment sector, Timberland Investment Management Organizations ("TIMOs") funded 65% of the acquisitions in YTD 2023, up from 2022. Since 2016, TIMO's have funded 56% of all transactions (by value). From 2013-15, TIMO buyers acquired 25% of US timberlands sold (by dollar), compared to 78% in the previous 13 years (2000-2012).
- **Explanation**: The REITs took advantage of record lumber prices and/or record PNW log revenues to fund acquisitions in the South in 2013-15 and again in 2020-22. With narrower mill margins, the TIMO's have stepped back in.
- **Implication**: Rising asset values during periods of rising interest rates narrow the implied equity risk premium being paid for timberlands. Since owning timberlands is obviously more risky than holding government bonds, there must be some other value component forcing valuations higher, such as Carbon plays or rosy price expectations. **See last quarter's Deeper Dive**.
- **Expectation**: REITs may continue to reinvest outsized profits in timberlands if prices rebound again, but that seems unlikely in the near-term as housing languishes. More likely, higher borrowing costs will more than offset Carbon sales, leading to more modest valuations.

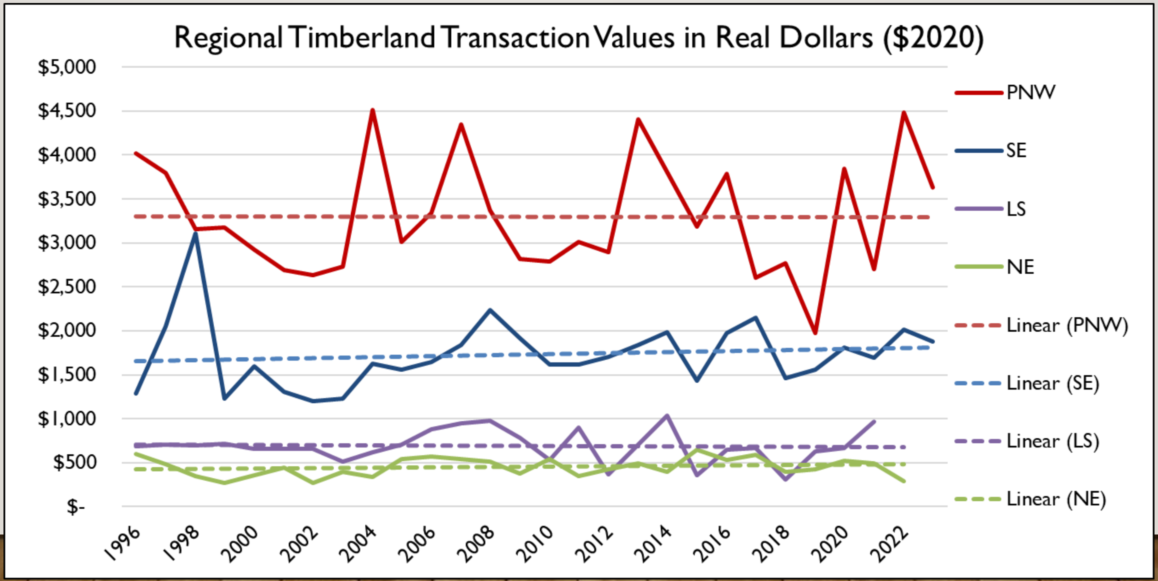
NE: Northeast LS: Lake States SE: Southeast PNW: Pacific Northwest Not Shown: Appalachia and Inland Northwest Data Source: TMS, TMR, Press Releases Charts & Analysis: WillSonn Advisory





BEHIND THE NUMBERS: TRANSACTION VALUES IN REAL $'S

- In real dollar terms, the PNW trendline has drifted sideways (~$8/acre) over the past 26 years, equivalent to a negative compound annual growth rate ("CAGR") of -0.1%
  - Some transactions in recent years have included lands in lower-value subregions. In addition, modest gains in productivity were likely offset by increased regulation limiting harvestable acres and/or volume.
  - The 2022 value shown on the previous page reflected two transactions, likely understating the downward trend.
- In the South, the real dollar trendline value has increased ~$150/acre over the past 26 years, a positive CAGR of 0.33%
  - Private softwood growing stock volumes are 32% higher (USFS: 2017 vs 1997), accounting for much of the increase in value. In addition, assumed near-term recoveries in stumpage prices have typified underwriting for years, despite evidence to the contrary.
- The Lake States real dollar timberland value trend through 2021 lost ~$30/acre (CAGR of -0.19%) while the value trend in the Northeast through 2022 gained ~$60/acre (a CAGR of 0.49%).
  - Both of these regions saw significant pulp mill contractions and modest gains in standing inventory, yet took different trajectories.
  - Conservation easements have been prolific in the Lake States, a possible factor as encumbered lands are subsequently sold.



SECTION 2: DEEPER DIVE

INDICATIVE CO_2e CONVERSION RATIOS FOR A SAMPLE OF REGIONAL TIMBER TYPES AND WOOD PRODUCTS

INTRO & DATA SOURCES

- Building on previous analysis, I developed a set of conversion factors to use with a variety of forests and wood products. A summary of my analysis is presented on the following pages.
  - Conversion factors for green tons of timber (one for timber inventory and one for harvested logs) and for various wood product groups in their common units of measurement.
  - While the conversion factors may or may not be of interest or use to many readers, the variances between species, timber types and regions suggest that various forests and wood products do not provide equal amounts of carbon storage.
- In prior Deeper Dives, I've referenced the 2006 USFS publication, General Technical Report NE-343, a great resource for estimating Carbon in a wide range of timber types across the US.
  - Citation: Smith, James E.; Heath, Linda S; Skog, Kenneth E.; Birdsey, Richard A. 2006. Methods for calculating forest ecosystems and harvested carbon with standard estimates for forest types in the United States. Gen. Tech. Rep. NE-343. Newton Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.
  - This report can be found at this link, along with the data tables in Excel format: Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States | US Forest Service Research and Development (usda.gov)
- In order relate common inventory and harvest volumes in green tons, to the figures found in GTR NE-343, I needed some additional information, most notably green tree moisture content. I found a comprehensive list in another USFS publication, GTR NRS-88.
  - Citation: Christopher W. Woodall; Linda S. Heath; Grant M. Domke; Michael C. Nichols, 2011, Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.
  - This report can be found at this link, along with a link to data files in Excel format: Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010 | US Forest Service Research and Development (usda.gov)

METHODOLOGY

- GTR NE-343 provides growing stock figures, in cubic feet per acre, and metric tonnes of Carbon content for each Carbon pool found in the forest.
  - There are six Carbon pools; Live trees, standing dead trees, understory, down and dead material, forest floor, and soil.
- Incorporating Species-specific moisture contents of live trees from GTR NRS-88, along with specific gravity and bark content figures found in GTR NE-343, I developed indicative inventory and harvest conversion figures (green, short tons to metric tonnes of CO_2 equivalents) for a number of forest cover type.
  - Moisture contents for various species ranged from 35% to 118% of Oven Dry Weight.
- GTR NE-343 also provided detailed wood product group allocations for each of four log classes (softwood and hardwood sawlogs and pulpwood) for each region.
  - There are eight Wood Product Groups; Softwood Lumber, Hardwood Lumber, Softwood Plywood, Hardwood Plywood, Oriented Strandboard, Non-structural Panels, Miscellaneous Products, and Wood Pulp.
- Using specific gravities for the species used in Wood Products produced in each region, I was able to develop region-specific CO_2e storage conversion rates for each wood product group.
  - Metric tonnes of CO_2e storage per wood product group unit of measure, at the time of production, and for a 100-year average storage (stored in use and in land fills).
  - Carbon contents for various wood products published by the USFS in other documents were not region specific, and in some cases, ignored the moisture content imbedded in their product weights (thus attributing carbon content to water).

CONVERTING TIMBER VOLUMES TO CO_2 EQUIVALENTS

- The indicative stocking figures below assume even age class distributions.
  - Stand ages ranged from 0 to 25 years in the southern pine forests, 0 to 50 years in southern hardwood forests, 0 to 45 years in PNW forests, and 0 to 65 years in northeastern and lake states forests.
- The indicative harvest levels represent volumes from clear-cutting at these rotation ages.
  - For each timber type, the USFS identified harvest volumes and product allocations for two log grades, for both softwood and hardwood trees found in each timber type (so, four log grades for each forest type).
- There are some obvious weaknesses in the underlying data and tables from GTR NE-343.
  - Not many timber types are managed on a single-entry, clear-cut basis. Commercial thinning in softwood stands, or selective harvesting techniques in hardwood stands, could change the product allocations at each harvest, which would result in different long-term storage outcomes.
  - Product and species allocations were based on industry data collected prior to publication in 2006 (some going back into the 1980's and 90's), so advances in silviculture, harvest recovery and product recovery, as well as allocations to various products by log grade, are likely outdated.
- Nonetheless, the figures below can be informative when comparing various forest types.

Converting Merch Inventory in Green Tons to Forest Non-Soil Metric Tonnes of CO_2e's	SE Loblolly Hi Prod	SE Loblolly Average	SE Oak Gum Cypress	SE Oak Hickory	PNW DF (High Prod)	PNW DF (Average)	NE Spruce Balsam Fir	NE Maple Beech Birch	LS Maple Beech Birch	LS White Red Jack Pine
Indicative Stocking: Green Tons/Acre	65	41	25	28	98	86	38	42	25	36
MT of Total Non-Soil CO_2e/Green Ton of Merch Inventory	2.08	2.55	3.75	3.63	2.99	3.41	3.37	3.86	4.86	3.28
Converting Timber Harvest in Green Tons, to CO2e Emissions and Storage										
Indicative Harvest: Green Tons/Acre	135	86	45	48	213	164	80	106	55	82
MT of Live Tree CO_2e/Green Ton of Harvest	1.36	1.51	2.95	2.96	2.00	2.23	1.45	1.58	2.46	1.90
MT CO2e Storage in Wood Products @ Time of Prod/G.T. Harvest	0.45	0.45	0.48	0.48	0.70	0.70	0.44	0.50	0.51	0.45
Percent of Live Tree CO_2e harvested initially stored in WP	33%	30%	16%	16%	35%	31%	30%	31%	21%	24%
MT CO_2e Storage in WP/GT Harv. Following Prod: 100-yr Avg.	0.23	0.23	0.25	0.25	0.44	0.44	0.17	0.26	0.29	0.24
Net Percent Long-term CO_2e Storage in WP	17%	15%	8%	8%	22%	20%	12%	16%	12%	12%
MT CO_2e Live Tree Emissions/GT Harvested: 100-yr Avg.	1.14	1.28	2.70	2.72	1.55	1.78	1.28	1.32	2.17	1.66
Percent of Live Tree CO_2e Emissions due to Harvest	83%	85%	92%	92%	78%	80%	88%	84%	88%	88%

CONVERTING WOOD PRODUCT VOLUMES TO CO_2 EQUIVALENTS

- The two sets of figures below represent storage of CO_2 equivalents at the time of product production, and the 100-year average storage "In Use" and "In Landfills" (what I call storage durability).
  - Storage durability varied widely, from an average durability of 81% for Oriented Strandboard, to 24% for wood pulp.
- Weaknesses in the USFS data.
  - The USFS assumed each product was equally durable in all regions of the US. This is not likely the case.
  - Since publication of GTR NE-343 (and the publication dates of the underlying research upon which it relied), applications for certain products have likely changed, as have recycling rates and the treatment of urban waste.
  - These weaknesses should be more of a concern for the long-term storage figures (the bottom set), less so for the conversion figures at time of production (the top set).
- Weaknesses aside, these figures should provide reasonable approximations, on a region-specific basis.

CO_2e Storage in Wood Products @ Time of Production	SE Loblolly Hi Prod	SE Loblolly Average	SE Oak Gum Cypress	SE Oak Hickory	PNW DF (High Prod)	PNW DF (Average)	NE Spruce Balsam Fir	NE Maple Beech Birch	LS Maple Beech Birch	LS White Red Jack Pine
Softwood lumber (MBF to tonnes of CO_2e)	1.33	1.33	1.30	1.29	1.29	1.29	1.04	1.04	1.05	1.14
Hardwood lumber (MBF to tonnes of CO_2e)	2.06	2.06	2.09	2.27	1.84	1.84	2.08	2.15	2.15	2.05
Softwood plywood (MSF, 3/8" basis to tonnes of CO_2e)	0.70	0.70	0.68	0.68	0.68	0.68	0.54	0.55	-	-
Hardwood plywood (MSF, 3/8" basis to tonnes of CO_2e)	0.74	0.74	0.75	0.82	0.66	0.66	0.75	0.77	0.77	0.74
Oriented strandboard (MSF, 3/8" basis to tonnes of CO_2e)	0.72	0.72	0.76	0.82	-	-	0.73	0.78	0.78	0.72
Non-structural panels (MSF, 3/4" basis to tonnes of CO_2e)	1.36	1.36	1.42	1.55	1.31	1.31	1.09	1.41	1.40	1.17
Other industrial products (Thousand Cubic Feet to tonnes of CO_2e)	23.49	23.49	23.63	25.67	22.84	22.84	18.63	24.05	23.79	20.28
Wood pulp (Bales (500 lbs, dried to 8% MC) to tonnes of CO_2e)	0.40	0.40	0.42	0.42	0.42	0.42	0.42	0.40	0.42	0.42

Long-term (100-yr average) CO_2e Storage in Wood Products	SE Loblolly Hi Prod	SE Loblolly Average	SE Oak Gum Cypress	SE Oak Hickory	PNW DF (High Prod)	PNW DF (Average)	NE Spruce Balsam Fir	NE Maple Beech Birch	LS Maple Beech Birch	LS White Red Jack Pine
Softwood lumber (MBF to tonnes of CO_2e)	1.01	1.01	0.99	0.98	0.99	0.99	0.79	0.79	0.80	0.87
Hardwood lumber (MBF to tonnes of CO_2e)	1.37	1.37	1.39	1.50	1.22	1.22	1.38	1.43	1.42	1.36
Softwood plywood (MSF, 3/8" basis to tonnes of CO_2e)	0.54	0.54	0.52	0.52	0.52	0.52	0.42	0.42	-	-
Hardwood plywood (MSF, 3/8" basis to tonnes of CO_2e)	0.50	0.50	0.51	0.55	0.45	0.45	0.50	0.52	0.52	0.50
Oriented strandboard (MSF, 3/8" basis to tonnes of CO_2e)	0.59	0.59	0.62	0.67	-	-	0.59	0.64	0.64	0.59
Non-structural panels (MSF, 3/4" basis to tonnes of CO_2e)	0.98	0.98	1.03	1.12	0.95	0.95	0.79	1.02	1.01	0.85
Other industrial products (Thousand Cubic Feet to tonnes of CO_2e)	14.80	14.80	14.89	16.18	14.40	14.40	11.74	15.15	14.99	12.78
Wood pulp (Bales (500 lbs, dried to 8% MC) to tonnes of CO_2e)	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10

ROOM FOR IMPROVEMENT

- There were a number of areas noted above, where the data needs to be updated to reflect current forest management and wood product manufacturing standards of production.
  - I would welcome the opportunity to collaborate with any of my readers, in applying current and/or company specific data, and inserting it into the framework I've developed for this analysis.
- In addition, I have recently come across a number of research documents that question the 50% Carbon assumption (and application).
  - Most if not all practitioners (including the USFS, companies preparing Carbon Reports, and forest-based carbon offset schemes) have assumed that 50% of the oven-dry weight of wood is Carbon, regardless of species or region. Critics claim this is an oversimplified assumption.
  - While the average across all species is quite close to 50%, extensive research shows that Carbon concentrations typically range from about 45% to 55% for most commercial species.
    - Softwoods tend to have higher Carbon concentrations than hardwoods, due to a higher lignin content. Likewise, early wood (the lighter wood between the annual rings) has a higher content than late wood (the rings), again, largely due to varying lignin contents relative to weight.
  - In addition, other researchers have found that oven drying wood samples tends to volatize some of the Carbon in wood, thereby understating the true amount of Carbon being held in living trees.
    - This understates the benefit of growing trees to remove atmospheric Carbon and understates the amount of Carbon emitted during drying in the manufacturing process.
  - Species-specific data has been around for decades. There is no good reason why more precise Carbon content figures cannot be used in analysis, carbon reporting and emission offset schemes.
    - A comprehensive data set can be found using this link: A global database of woody tissue carbon concentrations | Scientific Data (nature.com)
  - A few of excerpts from relevant research papers appear in the following section, In Case You Missed It.

GENERAL OBSERVATIONS

- Timber Volumes and CO_2e storage.
  - Hardwood forests tend to hold more CO2e's/Green Ton of merch timber inventory, compared to softwood forests.
    - However, softwood forests tend to grow more volume per acre, so the carbon removal capacity (removing CO_2 from the atmosphere) of softwood forests would tend to be higher on a per acre basis.
  - Forests in the US South tend to store less CO2e's per green ton of merchantable wood, owing to less carbon located on the forest floor and higher recovery rates of merchantable timber.
- Wood Products and CO2e storage.
  - As a whole, wood products produced from timber in the Pacific Northwest tend to store a higher proportion of Live tree carbon, both in the sort-term and long-term.
    - Southern hardwood forests stored the lowest proportion of forest carbon in wood products, and northeastern softwood forest products were the least durable, as a whole.
    - Higher wood pulp usage (South and Lake States) and a higher proportion of pulpwood size logs were the primary factors driving carbon storage and durability.
  - Softwood Lumber, Plywood and non-structural panels produced in the Northeast and Lake States stored less carbon, due primarily to lower wood weights (specific gravities), compared to the South and PNW.
  - The conversion rates from Thousand Board Feet to MT CO2e is higher for Hardwood lumber than Softwood lumber, primarily because hardwood lumber is assumed to be traded rough-cut (full measure) rather than finished (~32% air).
    - However, as noted on the previous slide, conversions are based on the widely used assumption that 50% of oven-dry weight is Carbon, for all species. In reality, hardwoods tend to have lower C concentrations than softwoods, which would partially offset the higher C estimated for hardwood lumber.
- There is more work to do, with further refinements within reach.
  - Updates to harvesting and manufacturing yields and recovery is needed and could result in materially different results.
  - Using species-specific Carbon concentrations to improve precision is also possible, with the availability of comprehensive data. The next iteration of my analysis will incorporate this information.
  - Please reach out if you would like a tailored analysis for your business or would like to contribute data.

CONCLUSIONS

- I was able to develop a set of conversion factors for various timber types and wood product groups produced in each region.
  - The regional differences are material but are unfortunately often overlooked by Carbon accountants. I also cleaned up the math by properly factoring in moisture content in finished products.
  - Conversion rates ranged from as little as 2.1 MT CO_2e's/GT of timber in high productivity Loblolly forests in the US South, to more than 4 MT of CO_2e's/GT of timber in some NE hardwood forests.
- The expected long-term carbon storage in wood products, as a percentage of the live tree carbon, is rather small and varies between regions and between forest types.
  - As little as 8% and as much as 22% of live tree carbon is stored in wood products, on average, over 100 years.
  - The corollary to this is that 92% to 78% of the carbon residing in a mature stand is emitted after it is harvested.
- While well managed forests can recapture the resulting emissions that occur at or soon after harvest, that process can take decades, a significant temporal dislocation.
  - The idea that wood products are "carbon neutral" ignores the fact that harvesting trees is human caused (anthropogenic) while tree growth is largely a natural process (would have occurred anyway, so non-anthropogenic), particularly in the northern forests of North America. To what extent is up to debate.
    - A recent report from Washington State University (WSU-Agribusiness-report-Indroneil-Ganguly21.pdf (wfpa.org)) concludes that well managed forests play an important role in mitigating Carbon emissions.
  - Using more wood than necessary (e.g., CLT in residential construction) in order to store more carbon in wood products is wasteful, drives prices higher, and is wrongheaded when it comes to reducing atmospheric Carbon.
  - As I have pointed out in the past, Wood Product Manufacturers that acquire all or a portion of their logs from third parties remain prohibited from reporting Scope 3 (upstream) CO_2e Removals under current GHG Protocols (while supplemental guidelines which may allow it are under consideration).
  - For now, the use of wood products produced from well managed forests is generally better than using their alternatives; concrete, steel and plastic. However, shifts towards renewable energy (as an energy source for producing these alternatives), greater recycling, and more efficient manufacturing processes could change this equation over time.

SECTION 3:

IN CASE YOU MISSED IT

A SINGLE SOURCE OF DATA FOR PRECISE CARBON CONCENTRATION ESTIMATES

A global database of woody tissue carbon concentrations

Mahendra Doraisami[1], Rosalyn Kish[1], Nicholas J. Paroshy[1], Grant M. Domke[2], Sean C. Thomas[3] & Adam R. Martin[1]✉

Woody tissue carbon (C) concentration is a key wood trait necessary for accurately estimating forest C stocks and fluxes, which also varies widely across species and biomes. However, coarse approximations of woody tissue C (e.g., 50%) remain commonplace in forest C estimation and reporting protocols, despite leading to substantial errors in forest C estimates. Here, we describe the Global Woody Tissue Carbon Concentration Database (GLOWCAD): a database containing 3,676 individual records of woody tissue C concentrations from 864 tree species. Woody tissue C concentration data—i.e., the mass of C per unit dry mass—were obtained from live and dead woody tissues from 130 peer-reviewed sources published between 1980–2020. Auxiliary data for each observation include tissue type, as well as decay class and size characteristics for dead wood. In GLOWCAD, 1,242 data points are associated with geographic coordinates, and are therefore presented alongside 46 standardized bioclimatic variables extracted from climate databases. GLOWCAD represents the largest available woody tissue C concentration database, and informs studies on forest C estimation, as well as analyses evaluating the extent, causes, and consequences of inter- and intraspecific variation in wood chemical traits.

[A global database of woody tissue carbon concentrations | Scientific Data (nature.com)]

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A SINGLE SOURCE … CONTINUED

Background & Summary

Forests play a critical role in the global carbon (C) cycle, with the world's forests storing an estimated 861 ± 66 Pg C across tropical (~471 Pg C), boreal (~272 Pg C), and temperate forest ecosystems (~119 Pg C)[1]. At the same time, C cycling in forested biomes is highly dynamic and transient, with estimates indicating that forests sequester between ~2.15 to 2.4 Pg C y^{-1} globally on average[1,2]. Throughout the 2000s, structurally intact old-growth forests accounted for ~0.85 Pg C y^{-1}, while C sequestration was ~1.30 Pg C y^{-1} in secondary forests[2]. Tropical regions are particularly important in sequestering atmospheric carbon dioxide (CO_2) in both regenerating[3–5] and intact forests[1,6,7]. Nevertheless, recent analyses from both temperate[8] and tropical regions[7] have indicated that the magnitude of C sinks in old-growth forests are declining.

The amount of C stored within, and transferred to and from, trees and forests have been estimated from field- or remote-sensing-based observations of tree attributes, which are used to obtain estimates of tree- or forest aboveground biomass (AGB)[1,9–12]. Estimates of AGB are then converted into C estimates by multiplying these values by a woody tissue C concentration, commonly referred to in the literature as a C fraction[13–16] (i.e., the mass of C per unit dry mass). Accurate woody tissue C concentration data are therefore critical in (1) accurately estimating terrestrial forest C budgets and sequestration rates[17], (2) estimating the C emissions associated with land-use change[18], and ultimately (3) informing decision-making related to the identification of forests with high C storage capacity[11]. Indeed, the Intergovernmental Panel on Climate Change's (IPCC) Tier 3 C accounting protocols suggests that a "specific carbon fraction…should also be incorporated" when estimating C stocks and fluxes in AGB[13]. Moreover, woody tissue C concentration data can be employed in studies on the abiotic or biotic predictors of variation in – and possible adaptive significance of – wood chemical traits across tree species[19,20], as well as evaluating the role that different sample extraction, preparation, and analytical methods have on wood C fractions[17]. Owing at least in part to a lack of large woody tissue C datasets, these research areas have received relatively little attention in comparison to other suites of plant traits[21].

To date, most C estimation and reporting protocols use generic approximations of woody tissue C concentrations (namely, an assumption that 50% of AGB is comprised of C[13]), which has led to substantial systematic errors in forest C estimates. For example, our recent analyses indicated that generic woody tissue C fractions

A SINGLE SOURCE … CONTINUED

overestimate C stocks by approximately 8.9% in tropical forests[19]. Similar issues exist for the accounting of C stocks and fluxes in dead wood, with recent analyses indicating that generic dead wood C fractions may result in dead wood C pools being overestimated by ~3.0 Pg C globally[22]. Although multiple studies evaluating woody tissue C concentrations in trees globally through field- or meta-analyses now exist[19,23–25], there is no single woody tissue C data repository to aid researchers in accessing and using these data.

To address these issues, we created and describe here the "Global Woody Tissue Carbon Concentration Database" (hereafter GLOWCAD[26]), which contains woody tissue C concentrations measured on live and dead tree tissues, spanning all forested biomes. By organizing and standardizing data from a range of taxonomic groups and woody tissue-types (described below), GLOWCAD represents a resource that helps improve our understanding of both global forest C dynamics and inter- and intraspecific variability in wood chemical traits. GLOWCAD only includes data from peer-reviewed sources. In addition to associated information on the taxonomic identities and woody tissue types for each woody tissue C data point, GLOWCAD includes geographical and associated bioclimatic data obtained from climate databases[27].

Data records in GLOWCAD are stored in 3 easy-to-use Comma Separated Values (.csv) spreadsheets (Fig. 1). All spreadsheets comprise plain text, with the first spreadsheet (titled "Wood Carbon Database") containing the core data (i.e., woody tissue C concentrations and related information), while the other spreadsheets provide descriptive supporting information including references (titled "References") and column descriptions (titled "Column Descriptions"). GLOWCAD has been made publicly available through the Dryad Digital Repository, with existing applications including studies on: (1) woody tissue C concentrations variation across live trees[19,23,25]; (2) variation in dead woody tissue C concentrations[22]; (3) relationships between woody tissue C concentrations and tree life-history strategies[19,22]; and (4) climate correlates of woody tissue C concentrations in trees[28].

EXCERPTS FROM A 2002 STUDY OF 41 NORTH AMERICAN TIMBER SPECIES

A reassessment of carbon content in wood: variation within and between 41 North American species

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Abstract

At present, 50% (w/w) carbon is widely promulgated as a generic value for wood; however, the literature yields few data and indicates that very little research has actually been done. C contents in heartwood of forty-one softwood and hardwood species were determined. C in kiln-dried hardwood species ranged from 46.27% to 49.97% (w/w), in conifers from 47.21% to 55.2%. The higher C in conifers agrees with their higher lignin content (~ 30%, versus ~ 20% for hardwoods). Wood-meal samples drilled from discrete early wood and late wood zones of seven of the forty-one species were also investigated. C contents of early woods were invariably higher than those in corresponding late woods, again in agreement with early wood having higher lignin content. Further investigation was made into freshly harvested wood of some species to determine how much volatile C is present, comparing oven-dried wood meal with wood meal dried at ambient temperature over a desiccant. C contents of oven-dried woods were significantly lower, indicating that all past data on C content in oven- or kiln-dried woods may be inaccurate in relation to the true C content of forests. We conclude that C content varies substantially among species as well as within individual trees. Clearly, a 50% generic value is an oversimplification of limited application in relation to global warming and the concept of "carbon credits".

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[A reassessment of carbon content in wood: variation within and between 41 North American species - ScienceDirect]

EXCERPTS FROM A 2002 STUDY … CONTINUED

- Closing comments in the Discussion

A 1% difference in carbon content conceivably could have a significant impact on wood and pulp industries in relation to allocation of carbon credits within the Kyoto Protocol. The uncertainty (or, precision error) associated with our method was 0.5% (0.1% weighing, 0.4% leucine standard curve), and our observed differences in carbon of 9% therefore appear quite important. It could be argued that, all other factors being equal, additional carbon storage capacity per unit mass exists in softwood forests. However, this would be simplistic because many hardwood species have wood densities above 0.6 g cm^{-3} whereas softwoods in general are well below 0.6 g cm^{-3} [25,30]. Thus, high-density hardwood species, although having lower carbon content per unit mass than softwoods, will nevertheless contain the greater quantity of carbon per unit volume. Even disadvantaged hardwood species such as poplar, that have less than 50% carbon and also have low-density wood, if sufficiently fast growing conceivably could sequester more carbon than softwoods within a growing season. To estimate carbon content of forest stands, it is necessary to take into consideration not only the several kinds of wood within trees [39] but also stocking density (e.g. number of trees per hectare by age volume class). It is apparent from such considerations that accurate carbon inventories and management of forest ecosystem carbon pools will require much greater attention to detail than traditionally has been addressed by foresters. It is clear that much more research is needed, but from the preceding clarification, there is no doubt that a 50% generic value for carbon content is an oversimplification of limited application in relation to global warming and understanding the role of the forest as a carbon sink.

EXCERPTS FROM A 2016 STUDY: HOW WOOD SAMPLE PREPARATION AFFECTS MEASURED CARBON

The influence of preparation method on measured carbon fractions in tree tissues

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Carbon fractions of tree tissues are a key component of forest carbon mass estimation. Several methods have been used to measure carbon fractions, yet no comprehensive comparison between methods has been performed. We found significant differences between carbon fractions derived from four sample preparation methods: oven-drying, vacuum desiccation, freeze-drying, and a new method that consisted of (i) not drying samples, (ii) cutting samples instead of grinding them, (iii) measuring carbon content of samples, (iv) oven-drying remaining sample material and (v) using mass measurements of remaining sample material before and after oven-drying to adjust measured carbon fraction values to an oven-dry basis (minimize the loss of carbon (MLC) method). Oven-drying, freeze-drying and vacuum desiccation resulted in lower average carbon fraction estimates than the MLC method, suggesting that they do not capture as much of the carbon present in tree tissues. Further analysis showed significant, though small, differences in carbon fractions between powdered samples and samples excised from tree core segments with a razor blade. Powdered samples were found to have lower carbon fractions than the excised samples, indicating that some carbon is lost when samples are powdered instead of cut. Utilization of the MLC method captured an average of 1.4% more carbon on an oven-drying basis than freeze-drying, the next best method. Additionally, when applied to different tree tissue types, these methods measured different volatile carbon fractions, indicating that studies attempting to quantify volatile carbon and total carbon fraction in trees should measure all tissue types present.

influence of preparation method on measured carbon fractions in tree tissues | Tree Physiology | Oxford Academic (oup.com)

EXCERPTS FROM A 2016 STUDY … CONTINUED

Owing to the large amounts of biomass stored in forests, small changes to forest carbon fractions can lead to large changes in forest carbon mass estimates (Jones and O'Hara 2012). For example, an increase in the global wood carbon fraction from 50 to 51% would lead to a global carbon storage estimate that is ~7 petagrams (Pg) higher than that estimated by Dixon et al. (1994). This amount of carbon is equivalent to approximately half of the carbon stored in all forested areas in the continental USA (Dixon et al. 1994). This sensitivity of forest carbon mass estimates to small changes in estimated carbon fractions requires that carbon fraction measurements be as accurate as possible in order to ensure accurate forest carbon estimates. Given the chemical complexity of tree tissues, carbon fraction measurements should be obtained for all tree tissue types to develop representative whole-tree carbon mass estimates.

The significant differences between the tested methods are extremely important for the growing field of tree carbon analysis and its extension to tree, forest, landscape, regional and global scale carbon mass estimation. Our findings demonstrate that the MLC method more accurately represents carbon fraction in tree tissues in comparison with all other methods tested, and that carbon fractions in tree tissues are sensitive to a range of factors in addition to the effects of high heat from oven-drying determined by Lamlom and Savidge (2003). Given the varying results in species mean level C_c values in our study (Table 6) and in the literature (Lamlom and Savidge 2003, Thomas and Martin 2012*b*), it is possible that analyzing a different set of tree species could have led to different results. However, the findings of this study leave little doubt that there is a significant potential to underestimate carbon fractions using the most common preparation methods, including freeze-drying and vacuum desiccation.

Table 6. Mean carbon fraction percents for each species as measured by a given method. Mean carbon fractions were estimated by fitting carbon fraction data for each species to Eq. (2). Standard errors for the parameters are shown in parenthesis. Mean carbon values include all tissue types for a given species.

Species	Oven-drying (%)	Freeze-drying (%)	Vacuum desiccation (%)	MLC (%)
Douglas-fir	49.93 (0.35)	50.94 (0.37)	50.48 (0.39)	51.95 (0.38)
Giant sequoia	52.40 (0.35)	53.41 (0.37)	52.95 (0.39)	54.42 (0.38)
Incense-cedar	51.86 (0.34)	52.87 (0.36)	52.40 (0.38)	53.88 (0.37)
Jeffrey pine	50.67 (0.51)	51.68 (0.53)	51.22 (0.54)	52.69 (0.53)
Ponderosa pine	50.51 (0.24)	51.52 (0.27)	51.05 (0.29)	52.53 (0.28)
Red fir	49.97 (0.42)	50.97 (0.44)	50.51 (0.45)	51.98 (0.45)
Coast redwood	50.64 (0.37)	51.65 (0.39)	51.18 (0.40)	52.66 (0.39)
Sugar pine	51.56 (0.26)	52.57 (0.29)	52.11 (0.31)	53.58 (0.30)
White fir	49.58 (0.33)	50.59 (0.35)	50.12 (0.37)	51.60 (0.36)

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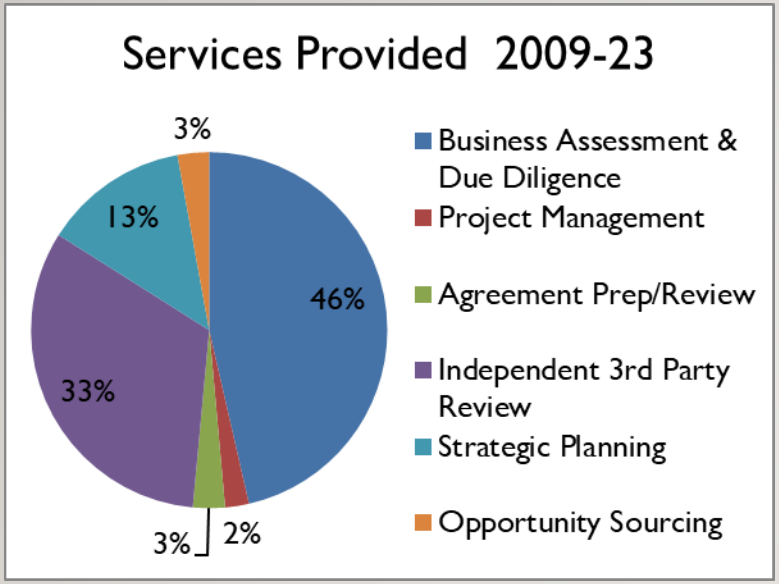

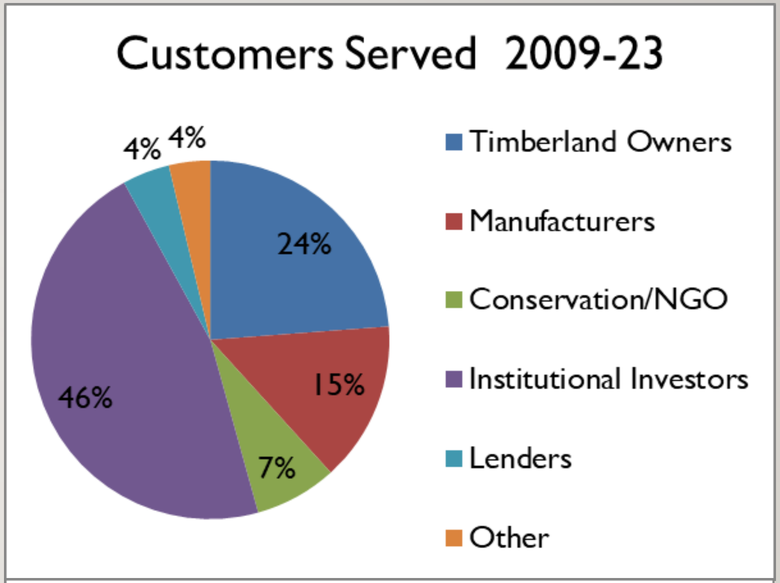

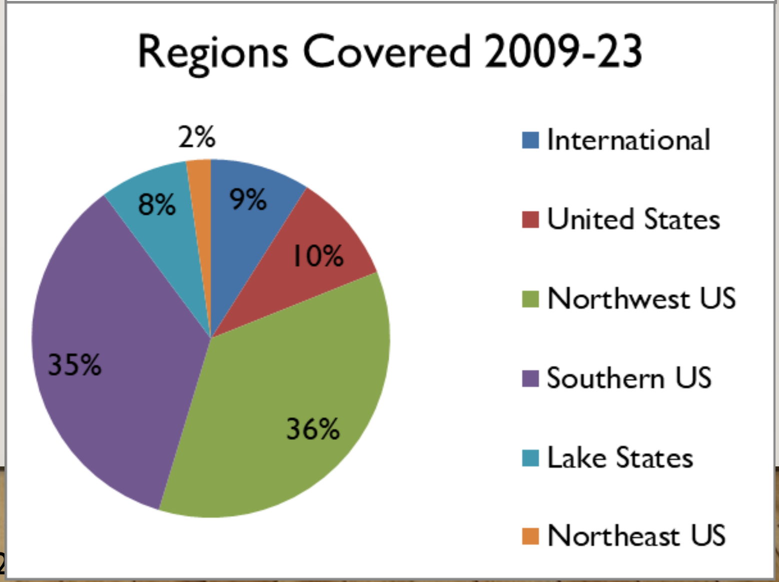

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I look forward to receiving any comments or questions you may have and would welcome the opportunity to serve your consulting needs.

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