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ORIGINAL PAPER

Roles of Growth and Yield Models for Informed Forest Management Decisions in the Pacific Northwest United States

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Abstract
This essay examines the important roles of growth and yield models in forest management decision-making in the Pacific Northwest United States. It outlines how these models help managers evaluate and optimize forest productivity on commercial timberlands by incorporating site indices, growth responses to silvicultural treatments like thinning, fertilization, and vegetation control, the potential impacts of climate change, and other factors. The essay reflects on how growth and yield models help forest managers optimize stand development, balance multiple objectives, and adapt to changing environmental conditions. It also analyzes key challenges, including limitations in site index estimation for young stands and areas without trees, the derivation and application of the maximum stand density index, complexities in generating initial tree lists, error propagation in long-term projections, and uncertainties in quantifying climate change impacts. Carbon accounting is an increasingly important consideration, highlighting how growth and yield models can help forest managers address new demands in carbon markets. Recommendations are provided to improve model accuracy and reliability in management applications. In conclusion, the essay underscores the necessity of enhancing model predictive accuracy while integrating technological advancements for sustainable forest management in the Pacific Northwest. It acknowledges the complex balance among productivity, financial returns, and conservation objectives in an evolving environmental and economic landscape.

Keywords Site productivity · Carbon sequestration · Climate change · Error propagation · Silvicultural treatments · Maximum stand density index

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Introduction

Forest products are essential to the global economy, and a predictable supply depends on a significant land base of productive and well-managed timberlands (Rodriguez et al. 2014). In the United States, timberlands comprise 67% of the 310 million ha (766 million acres) of forest land, with an estimated market value of $460 billion (Mei 2019; Newell and Eves 2009). The Pacific Northwest (PNW, Oregon and Washington) holds a substantial portion of these timberlands, producing approximately 34% of the country's softwood sawlogs. Coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is a dominant forest type in this region, occupying 44% of total timberland area in the PNW (Oswalt et al. 2019).

Given the importance of PNW timberlands for both timber production and broader ecosystem services, forest management decisions must balance multiple objectives, including environmental conservation and economic returns. However, management complexity in this region has grown due to land use conflicts, environmental regulations (Carle et al. 2020; Lambin and Meyfroidt 2011), and heightened risks of wildfire and climate change (Halofsky et al. 2020). Changes in forest ownership patterns further complicate decision-making, as new owners may pursue different management strategies in response to evolving market conditions and objectives. Meanwhile, increasing interest in carbon offsets underscores the need to reconcile timber production with additional ecosystem services such as carbon sequestration (Busby and Macpherson 2022; Mei 2023).

To address these challenges, growth and yield models have become indispensable tools for evaluating potential timber yields, forecasting future stand structures, and comparing alternative management scenarios. Whether empirical or process-based, these models provide insights into how forests might respond to different silvicultural treatments, environmental conditions, and economic uncertainties (Burkhart and Tomé 2012; Vanclay 1994; Weiskittel et al. 2011b). Despite the many existing growth and yield studies, a comprehensive review specific to the unique conditions, challenges, and applications in the PNW is lacking. This essay aims to address that gap for several reasons:

- No recent review focuses on growth and yield modeling in the PNW while accounting for the region's distinctive characteristics.
- By synthesizing relevant literature, we can strengthen collaborations between forest practitioners and research scientists, leading to more robust and consistent application of growth and yield models in operational forestry.
- Emerging motivations for forest management, including carbon projects, create new demands on growth and yield tools that may require different technologies or modeling approaches.

This essay will discuss the integral roles of growth and yield models in forest management decision-making, specifically focusing on PNW timberlands. It will address site productivity, the impact of silvicultural treatments, carbon sequestration potential, challenges in model accuracy, and the influence of climate change on timberland management strategies. Through these discussions, the essay aims to underscore the key role of growth and yield models in intensive forest management practices and investment decisions in the face of evolving environmental and economic landscapes.

Background and Pacific Northwest Context

Key Factors in Timberland Management

Forest management decisions in the PNW, including both ongoing operations and potential acquisitions, rely on accurate assessments of forest conditions and growth potential to ensure sustainable management and profitable returns on investment (Baral et al. 2016; Rutegård et al. 2003). These decisions require evaluating management alternatives while considering current forest conditions, silvicultural history, growth and yield dynamics, operational feasibility, market conditions, and financial risks. As summarized in Table 1, these elements provide a comprehensive framework that serves as an integrated checklist of stand inventory metrics, operational options, and market-risk indicators, helping forest managers balance profitability, sustainability, and broader forest management goals (Hiegel et al. 2020). By linking biological and financial factors, Table 1 also helps guide targeted data collection for scenario analysis.

Pacific Northwest timberlands include many steep slopes and variable topography. Generally, this topography is associated with a high risk of soil disturbance (erosion and compaction) and water sedimentation, resulting in more costly infrastructure to access rural land (Chase et al. 2019). The risk of wildfires in PNW timberlands is a growing concern due to climate change, land management practices, and the accumulation of fuels in the forests. Summers are becoming hotter and drier, drying out the vegetation, making it more flammable and extending the fire season (Halofsky et al. 2020). In September 2020, wildfires west of the Cascade crest in Oregon and Washington burned nearly 340,000 ha (840,000 ac) in just two weeks, which nearly equaled the total area burned there over the previous fifty years (Reilly et al. 2022). Simulations indicate that burn probabilities across PNW forests west of the Cascade mountain range are projected to increase by 78% to 478% by mid-century, relative to the 1992–2020 baseline, while fire rotation periods are expected to decrease accordingly (Dye et al. 2024). Some studies have predicted that areas currently suitable for important commercial species may become less productive or suitable, which could greatly impact future timberland yields and management strategies (Kralicek et al. 2022, 2023; Weiskittel et al. 2012).

Timberland Resources and Ownership Trends

In the Pacific Northwest (PNW), timberlands are the essential source of timber and other ecosystem services (e.g., biodiversity, carbon sequestration, jobs), and effective management of these resources has become increasingly critical. The Forest

Table 1 Key components of an informed forest management decision

Key factors	Impact	Important considerations
Current Forest Conditions	Establishes the baseline for informed decision-making by detailing the present volume, quality, and structure of the forest	Accurate inventory surveys are critical. Incorporation of advanced technologies, such as remote sensing and lidar, can provide a more comprehensive assessment
Silviculture History	Affects current productivity and potential for future growth based on past management practices	Includes vegetation control, thinning, fertilization, genetic improvements, and other practices that influence stand dynamics
Growth and Yield	Provides forest growth and potential yield projections, supporting management and operational planning	Relies on accurate growth and yield models for projection. Forms the foundation for evaluating forest dynamics and long-term scenarios
Forest Operations	Determines operational feasibility and efficiency based on factors such as harvesting methods and logging logistics	Considers harvesting systems (e.g., ground-based vs. cable logging), log size and quality, and operational efficiency as influenced by growth and yield outcomes
Market Conditions	Influences decision-making through anticipated timber market prices, merchandising specifications, and haul distances	Requires analysis of local and regional market trends, species demand, and transportation costs
Other Operational Constraints	Impacts management decisions by imposing limitations beyond timber production	This includes easements, conservation goals (e.g., habitat conservation plans), staffing limitations, and supply chain bottlenecks that may restrict management options
Discount Rates	Accounts for financial risks and costs when evaluating long-term management decisions and investments	Incorporates the cost of capital, inflation expectations, and risks such as wildfire, pest outbreaks, or economic disruptions (e.g., mill closures)

Inventory and Analysis (FIA) program (Bechtold and Patterson 2005) defines timberland as unreserved productive forest land that is capable of producing more than 1.4 m^3/ha/year (20 ft^3/ac/yr) of industrial wood (Burrill et al. 2021). The forests of the PNW comprise 17% of all planted timberlands, producing about one-third of softwood sawlogs in the United States (Oswalt et al. 2019). Whether made by companies, agencies, or other timberland owners, forest management decisions must balance multiple objectives, including timber production, environmental conservation, and economic returns. The challenge of managing these lands has grown more complex due to various factors beyond environmental considerations, such as land use conflicts and environmental regulations. In the last forty years, the largest percentage change among major land uses in the PNW was an increase in urban area between 1982 and 2012, with urban areas in Oregon and Washington increasing by 53% and 73%, respectively (Bigelow and Borchers 2017). During the same approximate period, privately held timberlands decreased by 6% or 445,000 ha (1.1 million acres) between 1977 and 2017 (Oswalt et al. 2019). This trend affects both timberland acquisition and ongoing forest management decisions, as the availability of suitable land for timber production becomes increasingly limited. When forestland changes ownership, new management strategies must be developed to address changing market conditions and multiple objectives. Prices reflect increasing demand for a decreasing supply, particularly as competition for land use is shared among various sectors, such as agriculture, industry, and conservation (American Forest Management 2024; Kanowski 2003; Powers 1999).

Carbon Market Developments

Carbon markets have grown significantly worldwide, reaching approximately $1 billion in 2021, a 190% increase over the previous year (Ecosystem Marketplace 2021; World Bank 2022). As of 2021, nature based credits, including afforestation, reforestation, avoided deforestation, and improved forest management, now account for over half of global transactions (Busby and Macpherson 2022; Mei 2023). In the PNW, this momentum has accelerated with major policy initiatives, new market standards, and rising carbon credit prices. For example, Washington's cap-and-invest auctions created by the Climate Commitment Act have generated more than $2 billion since launching in 2023 (Washington State Department of Ecology 2025).

Forest carbon markets operate through three main pathways: compliance markets, voluntary markets, and incentive programs (Putney et al. 2023). Compliance markets, such as California's cap-and-trade program (California Air Resources Board 2024), require regulated emitters to offset emissions under strict protocols, often yielding higher credit prices (Kline et al. 2009; Latta et al. 2016; Rossi and Kuusela 2023). Notable PNW projects, registered with California's cap-and-trade program, include the Confederated Tribes of Warm Springs' 8,900-hectare (22,000-acre) project, launched in central Oregon (Ford and Zakreski 2020). Similarly, Green Diamond Resource Company acquired 257,000 ha (635,000 ac) of southern Oregon timberland in 2014, registered the lands in CARB's improved forest management (IFM) offset program in 2016 and 2017 (Green Diamond 2023; Rossi and Kuusela

2023), and sold about 250,000 metric tons of CO_2e carbon removal credits to Microsoft in 2021 (Green Diamond 2021). Voluntary markets provide flexible, usually lower-priced credits that corporations use to meet sustainability targets and signal environmental responsibility to stakeholders (Bayon et al. 2012; Lovell 2010). The Nisqually Carbon Project in Washington was the first forest carbon project in the PNW verified under California's offset protocol. Its 40-year management plan is designed to restore old-growth conditions, raise carbon stocks, and enhance habitat for listed species (Swedeen 2016). Similarly, Astoria's Bear Creek Watershed project generated over 260,000 credits through the American Carbon Registry (ACR) (City of Astoria 2015). In October 2024, Oregon's Department of State Lands enrolled the 33,600-hectare (83,000-acre) Elliott State Forest in the voluntary market to store up to 435,000 additional metric tons of CO_2e (Baumhardt 2024b; MIT Climate 2024). Finally, incentive programs for small forest owners operate across the PNW. Forest Carbon Works, already active in Oregon, enrolls parcels as small as 16.2 ha (40 ac) at no upfront cost to landowners, and Family Forest Carbon Program, developed by the American Forest Foundation and The Nature Conservancy are planning to expand to the PNW (Baumhardt 2024a).

As the market continues to expand in the PNW, growth and yield models play an increasingly important role in quantifying carbon storage, evaluating project feasibility, and guiding landowners under different forest conditions.

Current Growth and Yield Models

Growth and yield models are essential for predicting potential yields and evaluating management alternatives for a forest land base. These models provide a simplified representation of forest development over time, accounting for growth, mortality, and treatments. They can predict how a forest will develop under different conditions, such as contrasting management practices or environmental factors. Growth and yield models enable the comparison of forest management options, updates to forest inventories, and forecasts of future forest structures (Burkhart and Tomé 2012; Weiskittel et al. 2011b). Several different approaches exist to model tree and stand development, but they can be differentiated as empirical (conventional) or process (mechanistic) models (Taylor et al. 2009).

Empirical forest growth and yield models are developed using statistical analysis based on observed data to predict the growth and yield of forest stands over time. They require simple input data (e.g., tree heights, diameters, crown ratios, expansion factors, and species) to predict growth variables. Process models rely on understanding physiological, ecological, and biogeochemical processes, that influence tree and stand development. The main difference between empirical and process models is that empirical models describe the relationships between variables based on measurements taken from trees or stands, while process models represent physiological processes that influence tree or stand growth by understanding light interception, photosynthesis, respiration, etc., at the leaf or canopy level (Johnsen et al. 2001; Mäkelä et al. 2000). Process models aim to simulate the underlying mechanisms affecting stand growth and to understand causal processes, while conventional growth and yield models are used when the objective is prediction based on past and current conditions (Burkhart and Tomé 2012; Landsberg and Sands 2011; Vanclay 1994; Weiskittel et al. 2011b).

Table 2 presents a side-by-side summary of growth and yield models commonly used in the PNW, giving forest managers a clear basis for selecting the tool that best fits their objectives. Each model addresses different management objectives, geographic scales, and degrees of stand complexity. Because these differences strongly influence projections of volume, diameter and height growth, mortality and other stand attributes, choosing the right model is essential for reliable planning.

Factors Affecting Tree Growth and Yield

Site Productivity

Assessing site productivity is essential for determining its relative potential for wood production and creating a basis for silvicultural diagnosis and prescription (Burkhart and Tomé 2012; Vanclay 1994). In practical forest management, site productivity assessment should be unbiased, easily determined, and not affected by desired ranges of stand density when utilizing tree measurements (Bontemps and Bouriaud 2014). A quantitative estimate of site productivity is the most effective for modeling and forecasting. It highlights the importance of site quality in describing the relative productivity between stands and its use within growth and yield models. Directly measuring volume productivity is often not feasible due to scarce historical yield records from forested areas. As a result, an indirect measure, site index is commonly employed for site productivity evaluation (Skovsgaard and Vanclay 2008).

In the Pacific Northwest (PNW), site index estimates are often obtained by selecting a sample of "site trees" from a region of interest, such as a forest stand or stratum, which are trees of the dominant or co-dominant crown class and free of defect. Height and age measurements of the site tree are used as inputs into a regional site index curve that is typically fit for a specific species or forest type. Site index equations have a rich history of development in this region, spanning decades. Refer to Hanson et al. (2003) for a synthesis of some commonly used site index equations in the PNW.

Site index is a primary driver of most empirical growth models such as ORGANON and FVS, so its accurate determination is critical for modeling current and future timberland value (Fig. 1). Although Bruce's (1981) site index equations are widely used in the PNW, other equations are used to varying degrees, and conversion from one equation to another can be challenging, creating inconsistencies in timberland value estimates. Site index is most reliable when the stand age is near the equation's base-age, generally 25 or 50 years for coastal Douglas-fir plantations (Hann et al. 2006). Obtaining consistent estimates for younger stands is quite difficult, which propagates uncertainty into estimates of future value. In addition, site index is often a highly dynamic measure of site productivity as tree growth profiles change over time in ways not captured in current site index equations. Finally, future changes in site index and growth and yield projections are expected in the PNW due

Table 2 Growth and yield models used in the Pacific Northwest

Model name	Type of Model	Description	Reference
3-PG (Physiological Processes Predicting Growth)	Process Stand-level	3-PG was developed by Landsberg and Waring (1997). The model output shows the monthly growth period by calculating the radiant energy absorbed by forest canopies and converting it into biomass production. The model requires standard weather data, soil depth, and water-holding characteristics as inputs	Landsberg and Waring (1997)
CIPSANON	Empirical Distance-independent Individual tree-level	CIPSANON was developed by building on ORGANON's basic structure after the Center for Intensive Planted-forest Silviculture (CIPS) formation in 2009. It applies annual time steps and can start simulations from plantation age 0 based on measured or generated tree lists. CIPSANON focuses on intensively managed stands of Douglas-fir and western hemlock but has been most fully developed for intensive management of Douglas-fir plantations by incorporating the effects of competing vegetation control, thinning, fertilization, genetic tree improvement, and Swiss needle cast severity	Mainwaring et al. (2020)
DF.HGS (Douglas-fir Hybrid Growth System)	Hybrid (empirical and process) Individual tree-level	DF.HGS combines elements of empirical and process-based modeling approaches to refine local growth predictions. DF.HGS operates at an individual tree-level with an empirical architecture like ORGANON while representing crown dynamics at a fine scale, allowing for improved leaf area index estimation and detailed examinations of log yield and grade (Weiskittel et al. 2006). The model requires tree-level inventory data as well as standard weather data, soil depth, and water-holding characteristics as inputs	Weiskittel et al. (2010)
FPS (Forest Projection and Planning System)	Empirical Distance-dependent Individual tree-level	FPS was developed by Forest Biometrics Research Institute (FBRI). There are 74 organizations supporting the FPS and FBRI across North America (Forest Biometrics Research Institute 2021)	Arney (2016)

Table 2 (continued)

Model name	Type of Model	Description	Reference
FVS (Forest Vegetation Simulator)	Empirical Distance-independent Individual tree-level	FVS was developed and supported by the USDA Forest Service. More than 22 variants represent conditions in the United States; one variant is for British Columbia, Canada. The British Columbia (BC), ORGANON Southwest (OC), ORGANON Pacific Northwest (OP), Pacific Northwest Coast (PN), and Westside Cascades (WC) variants cover the Pacific Northwest region	Dixon (2002)
ORGANON (ORegon Growth ANalysis and projectiON)	Empirical Distance-independent Individual tree-level	ORGANON was developed by Oregon State University and uses a five-year growth period. The model has variants specifically developed for Southwest Oregon (SWO), Northwest Oregon (NWO), intensively managed plantations Douglas-fir plantations throughout western Oregon, Washington, and SW British Columbia (SMC), and red alder plantations (RAP) in Oregon and Washington	Hann (2011)
TASS (Tree and Stand Simulator)	Empirical Distance-dependent Individual tree-level	TASS was developed and supported by the British Columbia Ministry of Forests, Canada. The model represents each tree crown to predict growth. TASS is driven by height growth and crown-solar exposure factors, while many other models are driven independently by diameter and height growth (e.g., ORGANON and CIPSANON)	Mitchell (1969, 1975)

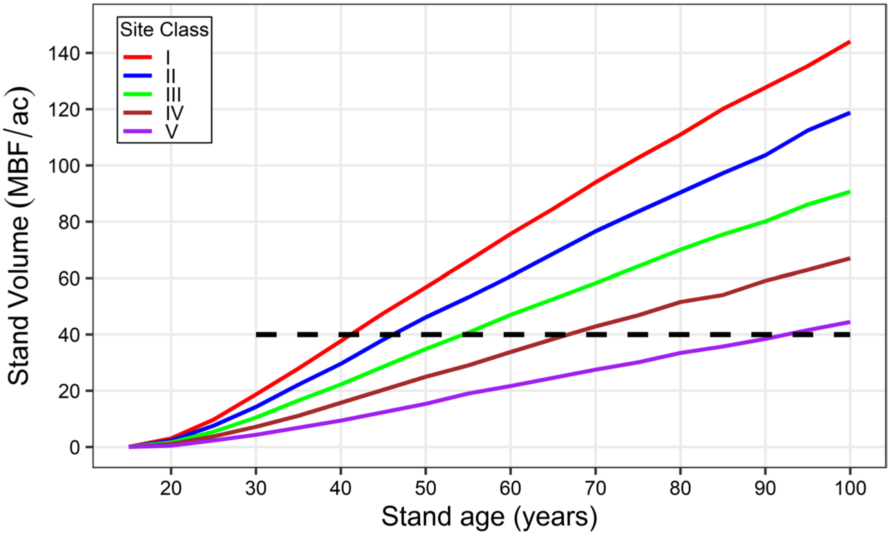

Fig. 1 Simulated cumulative growth in stand volume (MBF/ac) for Douglas-fir site classes I, II, III, IV, and V under 435 trees/ac using ORGANON. The dashed black line represents the 40 MBF/ac threshold harvest level. Note the implied range in harvest ages

to climate change (Weiskittel and Li 2012; Weiskittel et al. 2011b), which can be accounted for in future projections of timberland. For example, FVS incorporates climate change using its Climate-FVS extension, which modifies the intrinsic components of the base FVS model to reflect the impacts of changing climate on growth, mortality, and regeneration potential (Crookston et al. 2010). Users of Climate-FVS could input future climate data derived from downscaled outputs of General Circulation Models (GCMs), such as those used in IPCC (Intergovernmental Panel on Climate Change) assessments. These data include specific scenarios like RCP (Representative Concentration Pathway) 4.5, RCP 6.0, and RCP 8.5 to simulate potential future climate conditions. While FVS does not adhere to a single consensus on future climate, it enables users to evaluate a range of climate scenarios, providing flexibility to assess how different trajectories may influence forest dynamics (Crookston 2014).

The maximum stand density index (SDI_{MAX}) is often used alongside site index in forest management to quantify the carrying capacity for an even-aged stand under a given set of environmental and silvicultural conditions (Reineke 1933). In the PNW, this metric complements site index by describing how competitively trees can be packed on a given site once height growth potential is known. Early regional guides relied on the generic Reineke relationship and a constant slope of −1.605, but recent analyses show that both the slope and intercept vary by species and site conditions (Comeau et al. 2010). Consequently, SDI_{MAX} should be treated as a site-sensitive attribute, rather than as a single constant for each species.

Heiderman and Kimsey (2021) analyzed 168,000 plots in western Oregon and Washington, using quantile mixed and stochastic-frontier models. They estimated site-adjusted SDI_{MAX} at about 1,728 trees/ha (700 trees/ac) for Douglas-fir and 1,952 trees/ha (790 trees/ac) for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), with self-thinning slopes of −1.517 and −1.461, respectively. SDI_{MAX} increased on cooler, moist sites with high growing-season precipitation, at higher elevations, and where volcanic-ash soils enhanced water-holding capacity, but it declined toward northern latitudes and on sandstone or glacial parent materials (Heiderman and Kimsey 2021; Kimsey et al. 2019). Mixing in more shade-tolerant species such as western redcedar (*Thuja plicata* Donn ex D. Don) or western hemlock further elevated SDI_{MAX} relative to pure Douglas-fir, highlighting the importance of species composition in determining stand packing (Heiderman and Kimsey 2021).

Site index captures the vertical dimension of productivity by describing potential height growth of dominant trees at a reference age, whereas SDI_{MAX} reflects the horizontal dimension by quantifying the maximum number of trees per unit area for a given average diameter. Thus, site index drives potential height and volume growth, while SDI_{MAX} governs density-dependent mortality and guides thinning prescriptions. Both metrics are embedded in regionally calibrated growth models such as ORGANON and FVS. Used together, they provide a more complete depiction of site productivity and help forest managers balance stocking levels with expected height growth to optimize yield, carbon storage, and financial return.

Silvicultural Treatments

Understanding the history of silvicultural management in a forest is crucial for ongoing management and potential ownership transitions. Silvicultural management implies a long-term proposition that silvicultural treatments applied early- or mid-rotation can significantly affect future growth and yield. Therefore, when evaluating forest stands for management planning or acquisition, it is important to understand what types of treatments have been applied and their locations throughout the land base for accurate growth and yield projections. Past silvicultural management practices inform the selection of future management strategies and help determine suitable practices moving forward, which should be carefully considered when creating long-term forecasts (Pitt et al. 2013; Snowdon 2002).

Some common approaches used to represent silvicultural treatments in growth and yield models are: 1) separate equations for untreated and treated stands, 2) single equations with treatment predictor variables, and 3) treatment modifier equations. The modifier approach is used to adjust tree growth predictions in response to silvicultural treatments at either stand or tree levels. A treatment modifier equation acts as an adjustment to an existing prediction of untreated growth. It can be a multiplier (multiplicative modifier) or an additive factor (additive modifier) applied to the untreated growth predictions. A multiplicative modifier (i.e., multiplier) would typically alter the growth rate by a certain percentage, reflecting proportional changes due to treatment. Understanding how a growth and yield model accounts for silvicultural treatment effects is critical for ensuring proper estimation and valuation.

The following sections introduce a unified framework that details modifiers for thinning, fertilization, vegetation control, and genetic improvement, enabling managers to compare expected returns across treatments and align prescriptions with investment goals.

Thinning

Thinning is an important treatment for timberlands as it reduces stand density, giving the remaining trees more space to grow. By removing less healthy, damaged, or suppressed trees, thinning reduces competition for resources like light, water, and nutrients, allowing the remaining trees to put more energy into the growth of the tree bole (Aussenac and Granier 1988). Within a growth model, the quantitative effect of thinning on tree growth is usually adjusted with a multiplier on either tree diameter growth or basal area growth, boosting growth increments above and beyond that expected from reduced stand density and crown elongation. In addition, thinning treatments can be expected to reduce the probability of residual tree mortality (Marshall and Curtis 2002). The effects of thinning on residual trees depend on factors like stand structure, tree species, and crown size before thinning, with responses lasting well beyond post-treatment crown closure (Brix 1981; O'Hara 1988).

During the 1990s in the PNW, markets, timber supply, and manufacturing trends favored intensive management of Douglas-fir and western hemlock stands on large private ownerships for timber production, emphasizing higher internal rates of return from short rotation ages and smaller logs. While there are still limited market premiums for large logs, the longer rotations and commercial thinnings applied in producing such logs have been focused more on public lands (Curtis 1995). The last decade of the twentieth century in the PNW brought new demands for sustainable forest management, ecosystem services, social benefits, and forest certification, complicating traditional fiber-focused forest management strategies. Furthermore, thinning has become a key element in fire management strategies. Decreasing fuel loads can reduce the intensity and spread of wildfires, thereby protecting both the forest ecosystem and nearby communities (Agee and Skinner 2005). This practice has become increasingly relevant as the region faces more frequent and severe fire seasons due to climate change (Graham 1999; Harrod et al. 2009).

Thinning response multipliers (diameter and height increment) have popularly been used in tree-level growth models to adjust diameter and height increment based on thinning intensity and time since thinning (Kuehne et al. 2016). The diameter increment modifiers predict an increase in increment with an increase in thinning intensity (Cochran and Barrett 1993). In contrast, the height increment modifier predicts a decrease increment as thinning intensity increases (Ginn et al. 1991; Harrington and Reukema 1983). The cumulative effects of multiple thinnings on tree growth have been modeled by reducing the impact of earlier thinnings as they are projected forward to the time of the most recent thinning (Hann et al. 2003). By accurately accounting for the immediate and long-term effects of thinning treatments in growth and yield models, stakeholders can make informed decisions about the financial implications of a thinning program, the effects on the timing and value of wood production, and changes in the accompanying value of land.

Fertilization

Fertilization on some sites increases the internal rate of return on timberland by adding nutrients, thereby promoting tree growth and improving overall forest productivity (Mainwaring et al. 2014). Approximately 1.5% of Douglas-fir plantations in the coastal PNW are fertilized annually, with historical estimates indicating that around 101,000 ha (250,000 ac) of these plantations have undergone fertilization since 1990 (Briggs 2007; Littke et al. 2014). Fertilization can address nutrient deficiencies and enhance growth, particularly in nutrient-limited environments, by supplementing the naturally available nutrients in the soil (Hopmans and Chappell 1994). Growth and yield projections that accurately reflect the response to fertilizer treatments are necessary to determine the best nutrient amendment prescriptions during various stages of stand development. Nitrogen (N) is generally the most limited nutrient required for sustainable tree growth since it's a primary component of amino acids, proteins, nucleic acids, and enzymes (Binkley and Fisher 2019; Landsberg and Sands 2011). In the PNW, both natural and planted second-growth forests have shown N limitation to growth (Miller 1973; Peterson et al. 1984) due to the cool and moist climate that slows decomposition and mineralization, rendering N unavailable in sufficient quantities to maximize productivity (Binkley and Fisher 2019).

Fertilization directly affects growth, meaning trees that respond to fertilizer grow more than unfertilized trees with the same initial structural conditions. This direct effect is usually based on factors such as stem growth, initial diameter at breast height, total height, live crown length, stand structure (especially density and tree crown class), and site conditions before fertilization (Brix 1983; Miller et al. 1989; Peterson et al. 1984). Growth of responding trees and stands accelerates, and initial conditions for successive growth periods change over the years since fertilization. Fertilization also causes indirect responses by changing stand density, total leaf area, average tree size (Putney and Maguire 2021), or other stand attributes that affect growth potential relative to the initial unfertilized stand (Brix 1991).

The operational application of N fertilizer first began in the 1960s in the PNW to increase forest productivity, yield, and return on investment (Bengtson 1979; Talbert and Marshall 2005). Miller et al. (1986) reported that 1) at least 60% of the Douglas-fir stands positively responded to N fertilization in fertilizer trials in the PNW (British Columbia, Washington, and Oregon); 2) Douglas-fir stands were generally more responsive than western hemlock or mixtures of Douglas-fir and western hemlock; 3) fertilization accelerated mortality in unthinned Douglas-fir stands; 4) a rate of 225 kg N/ha (200 lb N/ac) applied as urea was generally the optimal dose for fertilizing Douglas-fir stands; and 5) the candidate stands for N fertilization must be selected based on site qualities, stand ages, timing, and volume gains necessary to meet desired economic return. Previous studies showed that increases in N availability from N fertilization generally last no longer than 5–10 years in Douglas-fir stands (Binkley and Reid 1985; Miller et al. 1989). Site quality has commonly been used as an indicator of N fertilization response potential, with low-productivity sites exhibiting the greatest proportional response.

Thinned stands on moderately productive sites are more likely to respond with greater volume growth than those on highly productive sites, particularly high site, unthinned stands (Brix 1992). Growth and yield models enable forest managers and investors to evaluate different fertilization scenarios, with the timing of treatment relative to the final harvest being critical to both maximize the marginal financial gains and minimize any volume losses due to increases in mortality. Given the strong role of climate and soils in response to fertilizer, hybrid models like 3-PG or DF.HGS may be a better alternative for forecasting the long-term effects, particularly since a high number of stands may be non-responsive.

Vegetation Control

After harvest, resources such as light, water, and nutrients are readily available, and early seral species use these resources to occupy the site (Flamenco et al. 2019). Competing vegetation control is important for the consistent survival and growth of crop trees at early ages (Cole and Newton 1987; Maguire et al. 2009; Nilsson and Allen 2003). Chemical herbicides have been the most effective vegetation management for timber production in the PNW, accelerating the growth of stands by two years or more relative to untreated stands (Newton and Preest 1988; Rose et al. 2006), both through resource focus on crop trees and a reduction in time wherein seedlings are susceptible to browsing damage (O'Dea et al. 2000). This investment has become increasingly prioritized over the past 30 years, during which the management objective of private timberland in PNW has shifted from "maximum yield" to "maximum return on investment" (Talbert and Marshall 2005). Herbicidal vegetation management has been broadly preferred by most private landowners in the PNW, with approximately 65% of Douglas-fir plantations on industrially managed lands receiving chemical site preparation (Briggs 2007; Maguire et al. 2009) due to its relatively low cost and high efficacy (Ketchum et al. 1999; Rose et al. 2006).

Using growth and yield models with vegetation management simulation capability provides the ability to predict long-term yield effects of different vegetation control intensities (Mainwaring et al. 2020) (Fig. 2) and different forest types (Wagner et al. 2006). Ritchie and Hamann (2006, 2008) developed the CONIFERS growth model for young stands, which includes growth equations for individual plant dimensions such as diameter, height, and crown width. The model simulates vegetation control by lessening the relevant type of crown closure.

Numerous herbicide trials have demonstrated that tree seedlings' diameter and height growth are improved with early competing vegetation control, particularly in moisture-limited sites where seedling survival is critical (Dinger and Rose 2010; Flint and Childs 1987; Rose et al. 1999). This improvement increases with declining competing vegetation cover and increasing length of the control period (Maguire et al. 2009; Rose et al. 2006). On sites with limited water availability in PNW, ensuring seedling survival often precedes achieving maximum growth. Although maximum tree growth may be achieved when all competing vegetation cover has been removed, the financial cost of such a treatment would be prohibitive (Talbert and Marshall 2005; Wightman et al. 2019). Growth and yield models, therefore, can provide a valuable tool for quantifying the potential estimated rotation-length growth benefits of different vegetation control strategies and predicting their impact on volume and financial yields from bare ground or young plantations. Like fertilization,

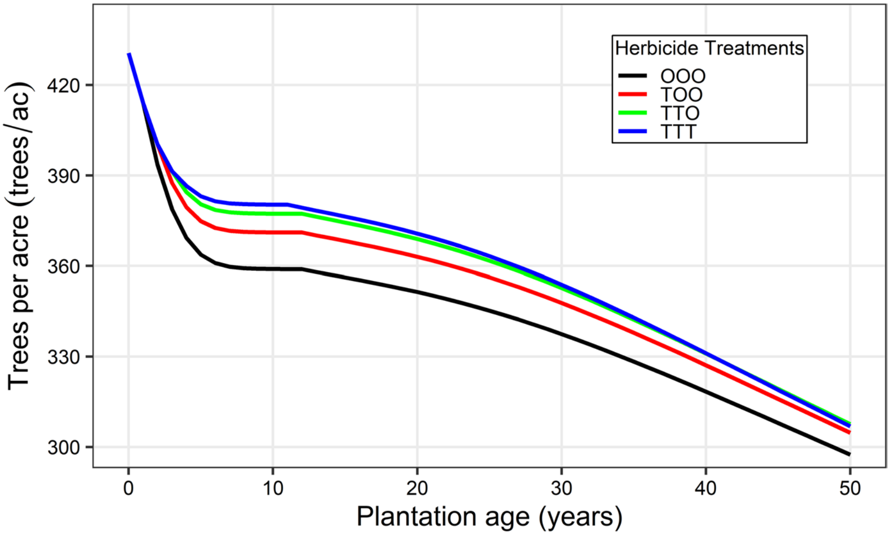

Fig. 2 Simulated effect of various herbicide treatments on the trees per acre of Douglas-fir stands with 435 trees/ac initial planting density using CIPSANON. No herbicide treatments after planting (designated as OOO), 1 to 3 consecutive years of release after planting (designated as TOO, TTO, and TTT)

response to vegetation control is highly variable due to various site factors, suggesting a more process model approach might be required for improved accuracy (e.g., Mason et al. 2007).

Genetic Improvement

Predicting the growth of genetically improved stands is important because faster growth and earlier biological rotation age may increase the return on investment in timberland. Douglas-fir tree improvement programs in the PNW began in 1954 (St Clair 2007; St. Clair and Howe 2017), and first-generation progeny tests were established in 1993 (Jayawickrama et al. 2005; Lipow et al. 2003). The program has progressed to a third cycle of testing and selection (Howe et al. 2006; Jayawickrama et al. 2017). All planted Douglas-fir seedlings are grown in nurseries from seed lots that represent some level of genetic improvement made possible by a large and virtually ubiquitous network of local tree improvement programs (Gould and Marshall 2010; Joo 2019; Talbert and Marshall 2005). These improved stands may also require different management regimes with respect to thinning and fertilization (Gould et al. 2008).

Two approaches have been used to incorporate genetic gain into growth and yield models: 1) site index adjustment and 2) genetic-gain multipliers. The site index adjustment approach involves adjusting the site index equation to reflect the rapid height growth of the genetically improved trees. The assumption with adjusting the site index is that there are no significant changes in stand dynamics, carrying capacity (maximum stand density), tree allometry, or height-diameter relationships with genetic improvement, so early age gains in site index are maintained during the rotation, which is a significant assumption that has large implications for long-term projections. In contrast, other studies (Adams et al. 2006; Xie and Yanchuk 2003) suggested that simply adjusting the site index is insufficient to represent a genetic improvement in growth models due to different genetic gains in diameter and height growth rates, respectively (Joo et al. 2023). The genetic gain multiplier approach uses a multiplier that adjusts the height or diameter increment by an empirical ratio of the observed growth of genetically improved seed lots relative to unimproved seed lots (Carson et al. 1999; Sabatia 2011). The approach of genetic-gain multipliers requires relatively little modification to existing growth models (Weiskittel et al. 2011b), simplifying operational implementations for forest managers. Gould and Marshall (2010) demonstrated how these genetic-gain multipliers and early expected gains could be incorporated into ORGANON and FVS under different levels of genetic gain, site productivity, and initial planting density. Joo et al. (2020) estimated a 3–5% gain in yield at 50 years by applying genetic-gain multipliers in CIPSANON using first-generation Douglas-fir realized gain trials measurement data at plantation age 17/18 years (Fig. 3). In practice, incorporating genetic improvements into growth and yield projections allows managers to fine-tune rotation lengths and more accurately forecast long-term returns on their timber investments.

Overall, growth and yield models represent the effects of varying silvicultural treatments in different ways, which can lead to high variability in projected outcomes. The implications of this are illustrated by Johnson (2005), who compared the long-term projections of various treatments and alternatives of thinning and fertilization from six commonly used growth models in the PNW. The analysis showed

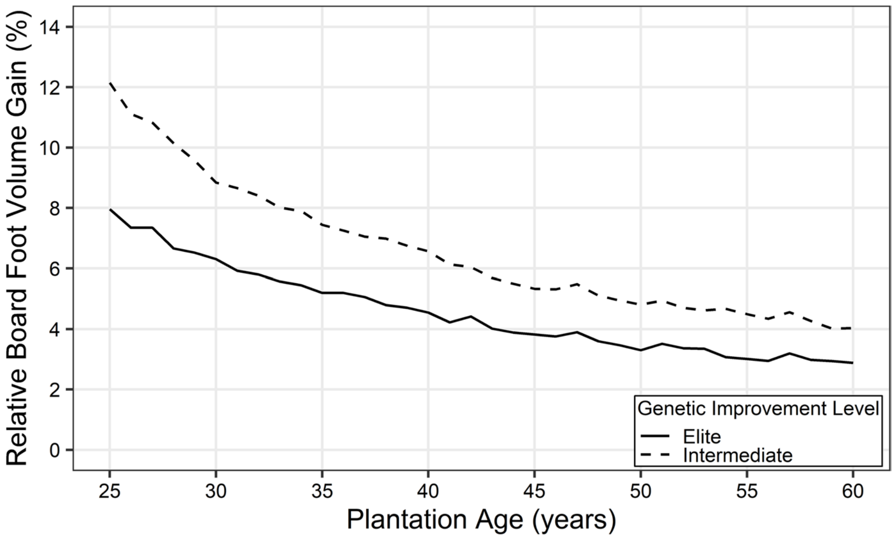

Fig. 3 Simulated relative gains of board foot volume averaged for the elite and intermediate populations relative to the unimproved population using genetic-gain multipliers in CIPSANON. Adapted from Joo et al. (2020)

the models had a wide range of responses to the treatments (up to 60%) with very few predictions adhering to the general research on the treatments, suggesting that users must be careful when making decisions based on model simulations (Johnson 2005).

Carbon Accounting

The dynamics of carbon accounting in forest ecosystems are of increasing interest due to the urgent need to mitigate global greenhouse gas emissions and combat climate change (Lubowski et al. 2006; Mei 2019, 2023). Forests in the PNW are significant in this context, serving as effective carbon sinks, both as highly productive ecosystems and long-lived forest products. Some of the most productive forests in the PNW are privately owned by industry or family owners (Rossi and Kuusela 2023), and these landowners can receive compensation for carbon storage. These forests are well-positioned to contribute to carbon offset programs, mainly through initiatives such as IFM projects.

The IFM has become the primary approach for forest carbon offset projects, focusing on management strategies that increase carbon stocks beyond typical practices (Kaarakka et al. 2023). Examples include extending rotation lengths and reducing harvest intensities to boost carbon storage while allowing some timber production (Haya et al. 2023; Randazzo et al. 2023). The foundation of IFM projects lies in demonstrating "additionality," which requires proving that management changes will result in greater carbon storage than in business-as-usual scenarios. This often requires establishing a baseline that represents common practice in the region, followed by implementing and documenting management practices exceeding this baseline (Ruseva et al. 2017). Projects must commit to maintaining these enhanced practices over extended timeframes, typically 20–40 years, ensuring long-term carbon benefits and environmental contributions (Putney et al. 2023).

Growth and Yield Model Selection and Calibration

Accurate forest carbon accounting in the PNW typically requires selecting an appropriate regional growth and yield models and calibrating it with local data. Widely used examples include the Pacific Northwest Coast (PN) variant of the FVS (FVS Staff 2008) and the FVS-ORGANON variant (Smith-Mateja 2015) for carbon simulation. However, using any FVS variant with its default settings can lead to systematic bias, especially in older stands, if growth and mortality parameters are not adjusted to match observed data (Diaz et al. 2018).

Research in the PNW shows that uncalibrated FVS variants often overestimate volume or carbon stocks, inflating projected yields (Diaz et al. 2018; Herbert et al. 2023). To address this, managers commonly compare model outputs against historical yield tables, permanent plot remeasurements, or forest inventory datasets, then fine-tune parameters such as basal area increment multipliers, maximum stand density index, or mortality functions. This approach can temper excessive growth projections, particularly for intensively managed Douglas-fir plantations, and align older stand trajectories with more realistic averages observed in FIA data or permanent plots. As a result, regional calibration and validation are essential steps to produce reliable carbon accounting projections.

Soil and Dead Organic Matter Carbon Pools

Accounting for soil carbon and dead organic matter is important for a full carbon budget, although most growth and yield models have limited capabilities in these areas. The FVS Fire and Fuels Extension (FFE) can estimate coarse woody debris and snags while combining fine debris and litter into a forest-floor category, generally treating soil carbon as static (Hoover and Rebain 2011; Rebain 2010). Management or environmental changes can alter decomposition rates, so omitting dynamic soil processes adds uncertainty.

One way to capture these pools more accurately is to pair a tree-growth model with a decomposition model such as CENTURY (Parton et al. 1987) or Yasso (Liski et al. 2005), or to use an integrated simulator like Canadian CBM-CFS3 (Kurz et al. 2009) that follows IPCC guidelines for aboveground, belowground, dead, and soil pools. Many forest offset programs (e.g., the American Carbon Registry and Climate Action Reserve) do not require soil carbon estimates in IFM if the land remains forested, though they do require estimates for standing and down dead wood (Haya et al. 2023). In the PNW, practitioners often treat soil carbon conservatively by excluding it from credit calculations or assuming minimal net change, given higher uncertainties compared to aboveground biomass (Gershenson and Barsimantov 2010).

Corporate Greenhouse Gas Emissions Reporting

Companies that own or manage forest lands are increasingly accounting for forest carbon flux in their corporate greenhouse gas (GHG) emission inventories. Growth and yield models enable such companies to track carbon emissions and removals associated with forest management, as part of their Scope 1 or Scope 3 emissions reporting. For example, Weyerhaeuser Company, a major timberland owner in the PNW, uses sophisticated inventory systems and proprietary growth models to calculate the annual change in carbon stored in its forests (Weyerhaeuser Company 2021). In 2020, Weyerhaeuser's managed forests sequestered a net 10 million metric tons of CO_2e from the atmosphere (i.e., net removal), as growth of trees outpaced harvest and natural losses (Weyerhaeuser Company 2021). This type of analysis uses the same data that support timber planning, namely periodic field inventories of tree diameters and heights. Growth and yield models extend those measurements to estimate biomass accumulation or depletion through time, producing a year-over-year carbon balance for the forest estate. When net growth is greater than removals from harvest and mortality, the forest acts as a carbon sink, an outcome companies can report as a positive contribution to their climate goals.

Growth and yield models also assist corporate reporting by attributing carbon changes to management activities. By simulating scenarios, a company can distinguish how much carbon gain resulted from planned growth versus how much loss resulted from timber harvesting or disturbances in a given period. Corporate GHG accounting frameworks, such as the GHG Protocol's land-use guidance, demand this level of rigor when quantifying emissions and removals. A growth and yield model can integrate data on tree growth, harvesting, and even disturbances like fire or pest outbreaks to provide this comprehensive carbon flux picture. In practice, companies may use FVS or similar models (sometimes customized to their lands) to update their forest carbon stock estimates annually. This approach ensures that company disclosures of forest GHG impacts are grounded in the best available science and data, lending credibility to claims of carbon neutrality or net-zero operations in the forestry sector.

Challenges in Applying Growth and Yield Models for Forest Management

Although growth and yield models support a broad range of forest management, important challenges remain. The following section highlights how factors such as site index, maximum stand density index, generating tree lists, error propagation, and climate change can complicate model accuracy in the PNW. Understanding these limitations is important for producing reliable projections that effectively guide management decisions for forest managers.

Estimation and Application of Site Index

Site index, a quantity based on the relationship between dominant tree heights and the age of the stand, is the most used measure of site productivity for forest management (Assmann 1970; Carmean 1975; King 1966). This is certainly the case in the PNW region, where site indices are frequently used as inputs into growth and yield models (e.g., Hann et al. 2006, FVS Staff 2008). While site index is extensively used, it does present certain limitations when used to measure productivity. Primary concerns include the following: 1) it is difficult to determine in very young stands; 2) it cannot easily be inferred in areas with no trees; 3) it can change over time for a given stand.

Estimating site indices for young stands is challenging for several reasons. First, height-age growth equations tend to be compressed at young ages due to the heteroskedastic variability of tree height as a function of age. This implies that determining site index using young trees is inherently difficult because even minor sources of error, such as measurement errors in age or height, will result in large errors for the site index estimate (Ni and Nigh 2011). Furthermore, young stands are often characterized by a highly dynamic growth phase where trees may exhibit varying growth spurts and changes due to variability in microsite conditions (Balandier et al. 2006), assuming that a single height-age curve fits tree development somewhat tenuous

(Flewelling et al. 2001). Site index equations are also frequently paired with a strategy for sampling site trees, often requiring surveyors to select trees free of defect and of the dominant or co-dominant crown classes (e.g., King 1966). Additionally, trees available for selection may not have yet reached a stage where dominant and co-dominant trees are distinctly identifiable in young stands.

Site index estimation often relies on utilizing pre-existing site curves, which take the height and age of existing site trees in the stand and produce a predicted site index value. In areas without trees, estimating the site index using this process is impossible, and forest managers must seek other means of estimating the site index, such as using historical records for the site or utilizing information from nearby areas. In the past few decades, landscape-scale site index prediction models, which relate wall-to-wall climate and topographic information to site index, have become an emerging solution for this problem (e.g., Koirala et al. 2021; Littke et al. 2016; Nothdurft et al. 2012). These site index prediction models can generate estimates of site index in areas without trees but are typically subject to large residual variances. In addition, hybrid growth models like 3-PG or DF.HGS can be used to generate high-resolution, localized maps of site index accounting for the potential effects of climate change (Weiskittel et al. 2011a).

Site index is not static and may undergo fluctuations over time for a given stand. Various factors contribute to these changes, including alterations in climate patterns, soil nutrient dynamics, genetics, or disturbances such as pest infestations and wildfires (Monserud et al. 2008; Raulier et al. 2003). Additionally, poor historical silvicultural practices, such as high grading, can result in misleading site index data by removing the most vigorous and high-quality trees, thereby underestimating the site's true potential productivity. As trees grow and environmental conditions shift, the actual growth patterns might deviate from initial predictions, necessitating site index adjustments to maintain accuracy. Adjusting site index over time is a challenging prospect, and recent developments in state-space modeling of site index using historical site index and climate data have yielded encouraging results (Yue et al. 2016). These methods can adjust site index over time using temporally indexed climate covariates and project site index values forward in time using information derived from general circulation models.

Maximum Stand Density Index Derivation

Deriving an accurate SDI_{MAX} requires empirical data on stands that have grown near their biological carrying capacity. In practice, such data are scarce because many stands are managed (e.g., thinned) before reaching extreme densities, or natural mortality intervenes stochastically. Large forest inventories often contain few plots right at the self-thinning boundary, making it difficult to fit the upper envelope of the size-density relationship. For example, Hann et al. (2011) examined 196 long-term red alder (*Alnus rubra* Bong.) plots in the PNW and found that only 15 approached the presumed self-thinning line. Even those were insufficient to reliably estimate the maximum-density line without fixing the slope parameter from literature. This illustrates how limited observations of fully stocked stands can lead to "unreasonable" parameter estimates for SDI_{MAX} if one naively fits the upper boundary. Measurement protocols can also bias SDI_{MAX} estimation. For example, if small trees are excluded, it can lead to under- or over-estimates of true stand density and bias SDI_{MAX}.

Even within a single species, maximum stand density can vary with site quality and environmental conditions, necessitating site-sensitive SDI_{MAX} models. In the PNW, researchers have explored incorporating variables like site index, climate factors, and topography directly into SDI_{MAX} estimation. Weiskittel et al. (2009) and Zhang et al. (2013) introduced site index as a covariate and significantly improved maximum stand density predictions, likely because climate and soil resources limit how many trees can coexist. A practical challenge lies in obtaining accurate environmental data for each plot. Location uncertainty can cause climate variables from a nearby grid cell to be substituted, introducing noise in the analysis. Thus, deriving SDI_{MAX} in the PNW often demands large data sets and requires model complexity.

Generating Tree Lists

Traditional individual-tree growth models rely on initial tree lists to establish the starting point for predicting future growth based on the trees' initial size distribution. A "tree list" is a detailed inventory of individual sample trees within a stand, which includes attributes such as species, DBH, height, crown ratio, and expansion factor (number of trees per unit area represented by the sample tree). These lists are traditionally obtained through ground-based field surveys, but more recently, they can be predicted using aerial laser scanning (lidar) combined with field plots and stand-level auxiliary information (Mauro et al. 2019). These tree lists are critical for simulating individual tree growth and projecting stand dynamics over time using growth and yield models. Tree lists form the backbone of empirical-based individual tree-level models, constituting the dominant type of growth and yield models in the PNW (Table 2).

Forest managers often make important decisions, especially when managing or evaluating timberlands, without the benefit of tree lists for recent clear-cut areas or stands with no previous (or available) measurements. Various tree list imputation methods, such as most similar neighbors, have proven effective in different forest landscape analyses (Moeur and Stage 1995). However, for simulating growth, generating a tree list representing planted seedlings from the initial 0–15 years is challenging. These challenges are due to the relative uniformity of seedlings contrasted with the fluctuating growth trajectories observed in individual trees during the early stages of a plantation. Accurately representing future stand structures and yield should be a key objective for managers since it can determine total stand productivity through variability in individual-tree resource acquisition.

For the first years after planting, the growth and differentiation of seedlings are significantly influenced by various elements. These include 1) silvicultural activities – including site preparation, harvest debris management, type of seedling container, skills of seedling handling, proficiency of the planter, competing vegetation control, and initial stand density (Mäkitalo 1999; Morris and Lowery 1988); 2) site type – including soil attributes, water holding capacity, evapotranspiration, slope and aspect, plant community type and planting micro-site; and 3) tree characteristics – including genetic traits, overall health and nutritional condition, and potential damage to seedlings among others (St. Clair and Adams 1991). It is almost impossible to model the effects of these factors as deterministic mechanisms because it is not feasible to measure them all and because the current understanding of their effects and interactions is poor. Instead, the effects of all these factors would contribute to the error term from the regression models. One consequence is that growth and yield models will always return the same outputs for a given set of measurable predictor variables used as inputs into the model.

The differentiation process has a large stochastic component through the early stages of stand development. However, the portion of the variation that can be predicted from initial tree, stand, and site conditions increases as the trees mature. Some studies (Stage and Wykoff 1993; Uranga 2020; Van Deusen 1984) showed that introducing stochasticity into the stand simulations during the first five initial years of plantation improved model performance. Uranga (2020) reported by incorporating stochasticity in the models during these first five years successfully reproduced observed patterns of rank changes in height over time, DBH distribution, and the improvement of multimodality of the DBH assignment procedure (where each tree is assigned a DBH when it reaches above breast height or 1.37 m) for Douglas-fir plantations. Also, including competing vegetation history into DBH and height distributions for generating Douglas-fir tree lists more realistically represented young stand size structures. It improved the ability of growth models to forecast future stand structures (Uranga 2020).

Error Propagation

In forest management, a complicated task that forest managers constantly struggle with is the issue of error propagation and measurement errors. These errors can originate from various sources, such as inaccuracies in data collection, model errors, and sampling errors (Canavan 2001). As these errors propagate through the different layers of analysis, they have the potential to significantly misrepresent the forest's true growth potential, volume, biomass, health, and, ultimately, its valuation. Consequently, identifying, quantifying, and mitigating these errors become important for making informed management decisions.

One of the primary challenges of addressing measurement errors is the accumulation of small inaccuracies that can substantially alter growth and yield projections. These minor discrepancies may culminate in substantial deviations from the actual values when magnified over large, forested areas or for long forecasts. For instance, slight errors in measuring tree heights or diameters can eventually lead to significant miscalculations in site index and volume estimations (Hasenauer and Monserud 1997; Ni and Nigh 2011). Errors in assessing site index can misguide understanding of potential site productivity and affect the success of long-term forest management strategies.

Dealing with error propagation becomes particularly challenging when integrating various data sources and models in forest management analysis. Different datasets might come with their own errors and uncertainties, which can compound when combined. When these data are used (i.e., input data) for predicting future developments using growth and yield models, the data errors lead to significant prediction errors (Mowrer and Frayer 1986). The consequences of these errors can cause errors in harvest timing, leading to economic losses. In addition, growth models themselves can have high prediction uncertainty even without any measurement error due to how they are constructed and the relatively low variability they can explain in the fitting process used (e.g., Wilson et al. 2019). An illustrative example of this challenge is the variability in growth and yield predictions generated by different forest growth models. Weiskittel et al. (2016) compared multiple Douglas-fir growth and yield models and demonstrated a wide range of predicted stand volume increments across varying site indices without any silvicultural treatments (Fig. 4). This result underscores the inherent uncertainty in model-based predictions, even when measurement errors are not considered. The divergence in predicted outcomes highlights how models themselves can propagate errors into management decisions. Consequently, it is essential to account for all potential sources of uncertainty and include them in estimates of both current and future timberland value.

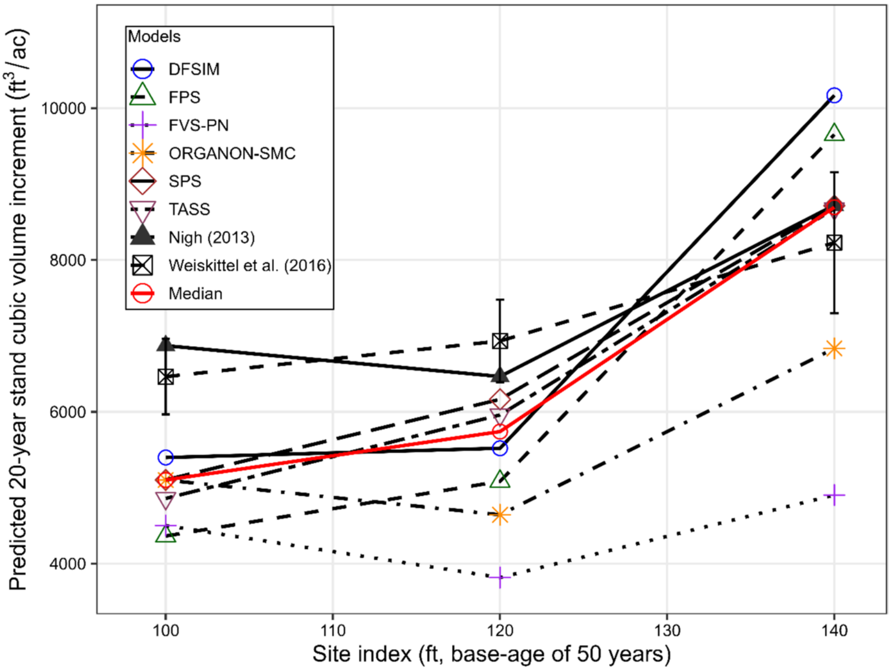

Fig. 4 Predicted 20-year stand cubic volume increments (ft^3/ac) for Douglas-fir stands across a range of site indices (ft, base-age 50 years), as generated by multiple growth and yield models, including DFSIM (Douglas-fir Simulator; Curtis 1981), SPS (Stand Projection System; Mason, Bruce and Girard, 1988), Nigh (2013), and all other models are described in Table 2. Error bars for Weiskittel et al. (2016) represent standard deviations of the predicted volume increments. The red line indicates the median predicted volume increment across all models for each site index level. Adapted from Weiskittel et al. (2016)

Quantifying Climate Change

Climate change poses an unprecedented challenge in forest management. First is the challenge of data adequacy and accuracy (Yousefpour and Hanewinkel 2016). The study of climate change is an evolving field, and incorporating up-to-date climate data such as temperature variations, precipitation patterns, and extreme weather events into traditional empirical growth and yield models is a complicated task. Climate data is often only available at coarse spatial scales, making it difficult to downscale and apply at the stand level, where microclimatic conditions might significantly deviate from broader regional trends.

Another significant obstacle is climate change impacts' inherent variability and unpredictability (Monserud 2003). Climate change can induce various effects on yield, including changes in growth rates, mortality rates, maximum carrying capacity, alterations in species composition, and increased susceptibility to pests and diseases (Keenan 2015; Medlyn et al. 2011), which can vary significantly depending on population genetics (Rehfeldt et al. 2018). Quantifying these multifaceted impacts requires sophisticated models integrating complex, nonlinear relationships and potential feedback loops. The timelines over which these impacts unfold can be protracted, adding another layer of complexity to the simulations and modeling process.

For forest management and timberland acquisition, the changing climate brings uncertainty that can affect the valuation, an inherent problem with forestry that increases with rotation length. A new modeling and simulation approach is needed to quantify how climate-induced alterations in forest growth dynamics and yield potentials might influence the long-term profitability of timberland assets (Guo and Costello 2013). Currently, mechanistic models like 3-PG and DF.HGS or modified empirical models like Climate-FVS (e.g., Crookston et al. 2010) are the best means for attempting to account for the complicated effects of climate change, which can have significant impacts on timberland value (e.g., Wang et al. 2023).

Reflecting on the challenges outlined, Table 3 summarizes the primary challenges in forest growth modeling and outlines recommendations for improving timberland valuation accuracy and reliability in the PNW.

Conclusions

Applied research into intensive forest management practices has resulted in impressive increases in forest productivity, and researchers have made laudable efforts to incorporate the predictive effects of these practices into forest growth and yield models. Of course, in evaluating a property's potential value, the resulting productivity gains mean little if the silvicultural treatments required to achieve them are not financially viable. Effective timberland management requires rigorous financial analysis and systematic evaluation of management options using growth and yield models. A property can be managed using many practices and methods, and growth and yield models are often utilized to analyze multiple scenarios and constraints. These models provide insights into how different management options influence outcomes, allowing forest managers to identify approaches that align with financial objectives and sustainability goals.

Table 3 Summary of challenges in forest growth modeling and recommendations for timberland valuation in the Pacific Northwest

Challenges	Key Considerations	Recommendations
Estimation and Application of Site Index	Site index estimation is challenging in young stands and impossible in areas without trees, but it is necessary for productivity measures	Use historical data, nearby area information, or landscape-scale prediction models for site index estimation in treeless areas. Adjust site index over time to reflect changing conditions
Maximum Stand Density Index Derivation	Accurate SDI_{MAX} estimation is difficult because few plots reach the self-thinning boundary, and the metric varies with site quality, climate, species composition and measurement precision, so naive fitting can produce biased parameters	Combine large inventories with site or climate covariates, stratify or model by site class, and, when upper-envelope data are scarce, constrain slope values with literature priors while checking plot locations to reduce bias
Generating Tree Lists	Tree lists are essential for simulating growth in empirical models but challenging to generate, especially for young plantations	Utilize imputation methods like nearest neighbors for tree list generation. Incorporate stochastic elements in early growth stages to improve model accuracy
Error Propagation	Measurement and model errors can significantly misrepresent timberland value	Integrate various data cautiously, acknowledging potential compound errors. Employ specific techniques and practices to minimize and quantify errors
Quantifying Climate Change	Climate change introduces variability and unpredictability in growth and yield projections	Utilize mechanistic or modified empirical models to account for climate impacts on forest growth and timberland value

Timberlands are often large holdings of many thousands of acres, accompanied by limited information about stands and their history. With a value based on future productivity and a range of value-added management actions, management options can be explored, and the primary tool for doing so is a locally-calibrated growth and yield model, but users need to understand the fundamental assumptions and challenges in applying these models in situations as outlined in this review.

Managing timberland in the PNW necessitates a multidimensional approach that integrates various factors affecting tree growth and yield. This essay has delineated the significant roles of growth and yield models in informing management decisions by evaluating potential impacts of site productivity, silvicultural treatments, carbon considerations, and climate change. To make informed decisions, stakeholders should leverage growth and yield models to evaluate different scenarios comprehensively, including assessing various silvicultural treatments and economic factors. The implications of climate change cannot be ignored, as it holds the potential to significantly alter forest dynamics or species viability, impacting growth and yields in the long term.

Optimizing carbon accounting, a critical aspect of mitigating climate change, hinges heavily on using growth and yield models to identify potential management regimes. These models not only aid in mapping the potential carbon storage capacities of various forest lands but also facilitate a balanced approach toward timber production and carbon sequestration. Understanding and effectively utilizing carbon allocation patterns can guide sustainable forest management strategies, harmonizing the goals of carbon sequestration and timber production.

The error propagation from various sources further complicates the management process, potentially leading to significant miscalculations and economic losses. Adding to this is the big challenge of quantifying the impacts of climate change and nonlinear relationships influencing forest growth dynamics. This calls for a re-evaluation and potential overhaul of existing models, introducing a new generation of simulations capable of deciphering the multifaceted impacts of climate change on timberland management.

In conclusion, growth and yield models play a key role in timberland management, assisting stakeholders in making informed decisions that can meet multiple objectives, including productivity and financial returns, while ensuring the sustainability of forest resources in the PNW. Future developments in these models should aim to enhance their predictive accuracy, integrating a wider array of variables and leveraging technological advancements to ensure more sustainable and profitable forest management. Combining advances in technology, such as remote sensing, Geographic Information Systems (GIS), and small area estimation (SAE), can enhance the accuracy and reliability of these models, providing more precise data for decision-making.

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