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ORIGINAL ARTICLE

Modifying Stand-level Growth under a Changing Climate using a Model Fusion Approach

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Abstract

The conventional growth models used in forest management often rely on historic biometric relationships and do not consider climate's impact on growth. Climate sensitive predictions of forest growth are essential to assess sustainable forest management and forest carbon, particularly under increasing climate change. In this study, we explored volume and stem biomass predictions from the climate sensitive, hybrid/process-based growth model 3-PG (Physiological Principles in Predicting Growth) for four tree species in British Columbia, Canada. Then, we used 3-PG to climate-adjust volume predictions from a conventional growth model without climate sensitivity. Yields from 3-PG and this model fusion were evaluated using repeated measurement plots. Stem biomass and volume predictions from 3-PG tracked the observed data, producing Relative Model Biases (RMBs) between 1 and -8% for lodgepole pine, subalpine fir, and interior spruce. Stem biomass and volume RMBs from 3-PG were approximately -15% for Douglas-fir. Climate-adjusted yields for the same projection period validated similarly to the conventional growth model. Long-term predictions of the model fusion were explored through year 2100 under three climate scenarios (low, medium, high). For plots on a moisture and temperature gradient, climate-adjusted yields increased volume predictions by 1-2% for lodgepole pine, 5-13% for Douglas-fir, 12-31% for subalpine fir, and 4-26% for interior spruce. For all species, climate-adjusted yields were moderated under drier conditions, and historically wet and cold plots experienced the greatest gains. This model fusion shows promise for supporting landscape-level timber supply and carbon accounting models that incorporate climate sensitive growth and decision-making based on site-level vulnerability.

Keywords Climate change · Adaptation · Forest growth · 3-PG · Hybrid model · Model fusion

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Introduction

Predictions of forest growth are crucial for sustainable forest management and allow for the evaluation of alternative silvicultural treatments (Hossain et al. 2022; Comeau and Bokalo 2024), the assessment of landscape-level management strategies, and the determination of long-term sustained yield (Lieffers et al. 2023; Lafond et al. 2024). Forest growth predictions are also essential for carbon accounting (Kurz et al. 2009; Griess et al. 2019a), the evaluation of post-disturbance recovery (Dempster and Meredith 2021), and the management of non-timber resources (e.g. Leston et al. 2020; Micheletti et al. 2021). Looking forward, reliable forest growth predictions will be essential to develop and apply new forest management strategies that rely on proactive, targeted, and quantitative silviculture (Achim et al. 2022).

Climate strongly influences how forests grow and develop, impacting characteristics like productivity (Monserud et al. 2008), diameter growth, competition (Oboite and Comeau 2020), and survival (Cortini et al. 2017). Climate also affects growing season length, evapotranspiration demand, and the prevalence of extreme weather events like heat waves, droughts, and frosts that can negatively impact growth (Price et al. 2013; Wotherspoon et al. 2023). At broader scales, climate influences the range of forest ecosystems (Rehfeldt et al. 2012; MacKenzie and Mahony 2021), the distribution of tree species, and the suitability of trees to their environment (Coops et al. 2011; Mathys et al. 2017). Climate change is also anticipated to alter environmental conditions, amplify extreme weather events, and place forests under increasing stress (Price et al. 2013; Wotherspoon et al. 2023), forcing changes to the distribution, suitability (Mathys et al. 2017; MacKenzie and Mahony 2021; Levesque and Hamann 2022), and growth of many tree species (e.g. Brecka et al. 2020; Boulanger et al. 2022).

Despite climate's central role in forest growth and development, the conventional growth models that inform forest management in Canada are largely based on historic empirical relationships with limited climate sensitivity, making these models unsuitable for predicting forests under climate change (Lieffers et al. 2020; Metsaranta et al. 2024). Empirical models are developed using correlative relationships based on mensuration data and are often accurate within the period and range of the fitted dataset (Landsberg 2003; Weiskittel et al. 2011). However, these models are unable to handle novel climatic conditions (Landsberg 2003; Lieffers et al. 2020), unless specified to incorporate climate modifiers (e.g. Crookston et al. 2010). Alternately, process-based models can provide insights into forest growth under climate change because they strive to operate mechanistically while incorporating physiological processes and principles that impact growth (Landsberg 2003; Weiskittel et al. 2011). This approach allows process-based models to be applied across varying environments and explore growth under novel climatic conditions in the future (e.g. Gupta and Sharma 2019). Although conceptually robust, process-based models can be challenging to parameterize, have prohibitive data requirements, or may not produce predictions with the same reliability as conventional growth models (Landsberg 2003;

Weiskittel et al. 2011). Hybrid models attempt to strike a balance between these two approaches, combining both empirical and process-based components to model forests under changing climatic conditions (Landsberg 2003; Kimmins et al. 2010). Hybrid models often employ parallel sub-models where at least one model element is mechanistic (Weiskittel et al. 2011). Unlike pure empirical models, hybrid models allow the exploration of changing ecosystem processes using the model's mechanistic components (Kimmins et al. 2010). Hybrid models may also have a lower calibration burden, fewer input requirements, and a partial foundation in established empirical relationships relative to pure process-based models (Kimmins et al. 2010; Weiskittel et al. 2011).

In British Columbia (BC), Canada, forests are ecologically, culturally, and economically important, encompassing 57.4 million hectares across a diverse landscape (Government of British Columbia 2021; Meidinger and Pojar 1991). On these forests, sustainable forest management is assessed using a suite of forest growth models, including the Variable Density Yield Projection (VDYP7) system (Government of British Columbia 2023). VDYP7 is a stand-level empirical model developed by the BC Government to support forest inventory updates and yield curve development for unmanaged stands with pure or mixed-species compositions (BCMFLNRORD 2019; Penner 2021). VDYP7's biometric relationships were fit using a large dataset that includes approximately 64,000 plots across BC (Government of British Columbia 2023). VDYP7 is closely linked to BC's stand-level inventory protocol and has been deployed to support landscape-level decision-making, sustained yield assessment, carbon accounting, and the evaluation of greenhouse gas emissions (Griess et al. 2019a, 2019b; Penner 2021; Metsaranta et al. 2023). Although trusted, extensively calibrated, and widely used in BC (Penner 2021), VDYP7 is not climate sensitive, and new approaches are needed to model forest growth under a changing climate (Metsaranta et al. 2024). Hybrid and process-based models could be used to directly model climate sensitive growth (e.g. Seely et al. 2015). However, hybrid and process-based models are often research based, coarsely calibrated, and have not undergone formal validation, thereby limiting their broad application (Metsaranta et al. 2024). A model fusion could address this issue, combining projections from different platforms and leveraging the strengths of each component to produce a better overall result.

In this paper, we develop a model fusion that incorporates climate sensitivity into VDYP7 projections using the climate sensitive, hybrid/process-based, and stand-level growth model 3-PG (Physiological Processes Predicting Growth; Landsberg and Waring 1997). To do so, we validate 3-PG for four commercial tree species in the BC interior using repeated measurement Permanent Sample Plot (PSP) data, graphical approaches, and simple statistics (Bokalo et al. 2013). Next, we prepare conventional VDYP7 projections using the PSP data and add climate sensitivity by applying a ratio adjustment based on parallel 3-PG simulations under a normal monthly climate (1961–1990) and a dynamic monthly climate. Then, baseline VDYP7 projections and climate-adjusted predictions are validated using the PSP data, graphical approaches, and the simple statistics that are applied to 3-PG. Finally, VDYP7 and 3-PG projections are extended through year 2100, and climate-adjusted predictions are evaluated across a moisture and temperature gradient under high, medium, and low climate change scenarios. 3-PG's physiological growth modifiers are also explored to explain climate-adjusted responses, and we discuss how this model fusion approach can be applied to support forest management across western Canada.

Materials and Methods

Study Area

The study area (Fig. 1) is located in the forested and commercially important Biogeoclimatic Ecosystem Classification (BEC) zones in the BC interior (Meidinger and Pojar 1991), including the Sub-Boreal Spruce (SBS), Sub-Boreal Pine—Spruce (SBPS), Engelmann Spruce—Subalpine Fir (ESSF), Interior Douglas-fir (IDF), Montane Spruce (MS), and Interior Cedar—Hemlock (ICH) zones. Forests within these BEC zones are diverse, occupy a range of sites and climatic conditions, and include significant components of lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), interior spruce (*Picea glauca* × *engelmannii*), and subalpine fir (*Abies lasiocarpa*) (Meidinger and Pojar 1991). Analyses will focus on these four dominant species (Fig. 1).

Growth Models

Variable Density Yield Projection (VDYP7)

As described above, VDYP7 is a stand-level empirical model that is primarily used to update BC's provincial inventory and prepare yield curves for unmanaged stands with pure or mixed-species compositions (BCMFLNRORD 2019; Penner 2021). VDYP7 employs height increment, basal area increment, and other biometric models to predict annual outputs, including stand-level volume, basal area, density, height, and quadratic mean diameter (QMD) at varying utilization levels (Government of British Columbia 2014; BCMFLNRORD 2019). Growth in VDYP7 is focused on a stand's primary, dominant layer with limited support for secondary or old "veteran" layers (Penner 2021). Succession and interactions between stand layers are not modeled (BCMFLNRORD 2019; Penner 2021). VDYP7 requires information about stand-level density (Trees with a Diameter at Breast Height (DBH) $\geq$ 7.5 cm), basal area (Trees with a DBH $\geq$ 7.5 cm), species composition (basal area percentage), age, measurement year, dominant height, crown closure, and BEC zone (Government of British Columbia 2014). Optional inputs include Lorey's height, stockable (forested) area, and vegetation cover (Government of British Columbia 2014). In addition, VDYP7 does not model very young stands, significant insect attack (a priori), ingress (a priori), silvicultural treatments, or climate-informed growth (Government of British Columbia 2014; BCMFLNRORD 2019; Penner 2021). All projections were run using VDYP7 version 7.19h.

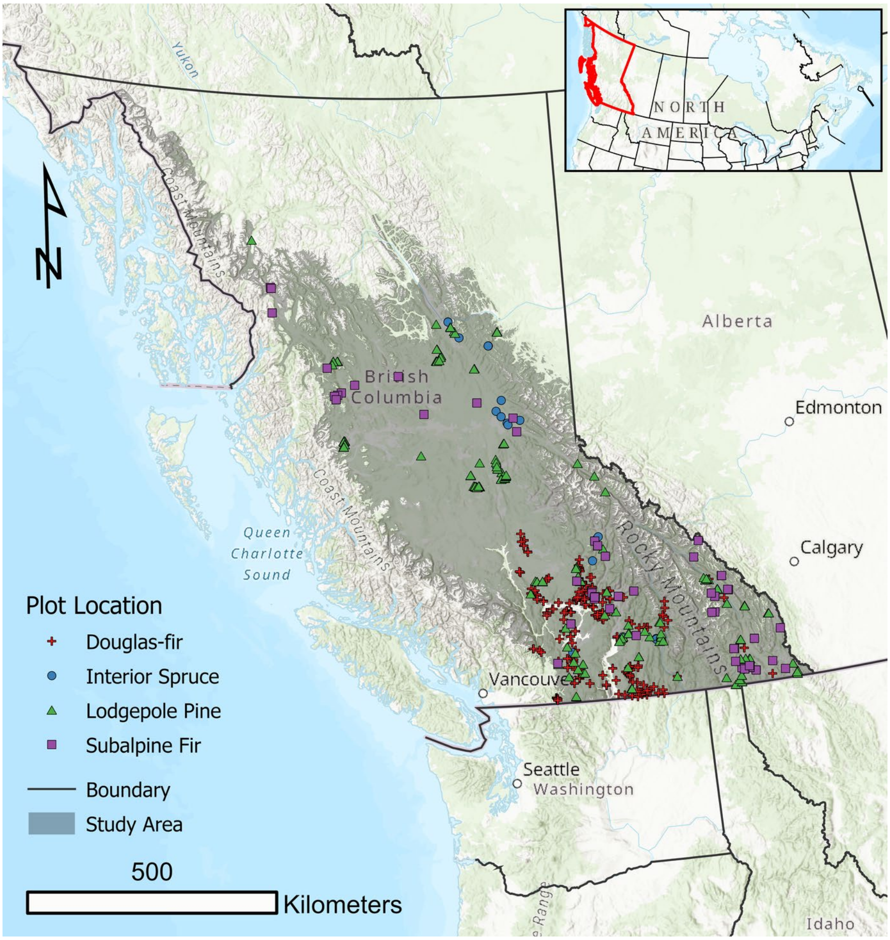

Fig. 1 Study area in British Columbia (BC), Canada. Permanent sample plot locations are identified by the dominant species. BC is highlighted in red within the inset map. [Boundaries: Open Government Licence—Canada; Basemap: ESRI, TomTom, Garmin, FAO, USGS © OpenStreetMap contributors in the GIS User Community, ESRI, USGS]

Physiological Principles in Predicting Growth (3-PG)

Physiological Principles in Predicting Growth (3-PG) is a hybrid/process-based stand-level model for evergreen, even-aged, and monospecific stands with climate and site sensitivity (Landsberg and Waring 1997; Weiskittel et al. 2011; Forrester et al. 2021a). 3-PG incorporates process-based and allometric components across five sub-models: biomass production, biomass allocation (stems, roots, foliage), soil water balance, mortality, and a sub-model that converts biomass information into management-oriented variables like stem volume and mean annual increment (Sands and Landsberg 2002; Gupta and Sharma 2019). 3-PG models growth (net primary production) on a monthly step based on a stand's radiation-use efficiency and the amount of Absorbed Photosynthetically Active Radiation (APAR) (Landsberg and Waring 1997; Gupta and Sharma 2019). APAR is adjusted using physiological modifiers that are related to vapor pressure deficit, available soil water, soil fertility, temperature, frost, and age (Sands 2004). These APAR modifiers reflect the growth characteristics of the target species, range from zero (no growth) to one (unimpeded growth), and are multiplicative, restricting growth relative to the most limiting modifiers (Sands and Landsberg 2002; Gupta and Sharma 2019).

3-PG requires information about stand biomass (stems, roots, foliage), density, soil texture, soil fertility, available soil water (initial state, site maximum), and latitude (Landsberg and Waring 1997; Trotsiuk et al. 2023). 3-PG also requires monthly temperature (min, max), precipitation, solar radiation, and the number of frost days per month. 3-PG's primary outputs are net primary production, stand biomass (stems, roots, foliage), density, available soil water, and transpiration (Sands and Landsberg 2002). Inferred management-oriented variables include leaf area index, basal area, mean diameter, volume, and mean annual increment (Sands and Landsberg 2002; Sands 2004). Additional information about 3-PG's structure and development can be found in Landsberg and Waring (1997), Sands and Landsberg (2002), and Gupta and Sharma (2019). The version of 3-PG used in this study (Landsberg and Waring 1997) does not model insect attack, mixed-species stands, or ingress (Gupta and Sharma 2019).

3-PG Calibration

We utilized recent 3-PG calibrations from du Toit et al. (2024) for lodgepole pine and spruce and Forrester et al. (2021a) for Douglas-fir. The Forrester et al. (2021a) parameters for *Abies alba* were applied to subalpine fir, given the species' physiological similarity. 3-PG projections were modeled using the r3PG package (version 0.1.6; Trotsiuk et al. 2020, 2023) in R version 4.4.2 (R Core Team 2024), based on the model formulation by Landsberg and Waring (1997) for evergreen, even-aged, and monospecific stands. To calibrate 3-PG volume, the bark and branch fraction of each species (fracBB0, fracBB1) were updated to match the range of the Ung et al. (2008) DBH-based biomass equations, and interior spruce wood density (rhoMin, rhoMax) was updated to match *Picea abies* in Forrester et al. (2021a). Maximum stand age (MaxAge) was set to 600 years for each species, allowing 3-PG growth at advanced ages and ensuring uniform age effects across species. Final r3PG parameters for each species are provided in the Supplementary Information (Table S1).

Environmental and Climate Data

Site, soil, and climate information were required to run 3-PG. Soil fertility and soil water storage capacity were informed using the satellite-derived layers developed by Coops et al. (2012) for western North America. Satellite-derived soil fertility and soil water storage capacity were used to demonstrate 3-PG's performance on sites without detailed, ground-based soil information. In locations where Coops et al.

(2012) soil fertility and soil water storage capacity were not available, soil fertility was assigned a default value of 0.5, and soil water storage capacity was assigned a default value of 200 mm (Coops and Waring 2011; Coops et al. 2011). All sites were assigned a default sandy loam soil, aligning with Coops and Waring (2011) and Coops et al. (2011). In aggregate, the default soil fertility, soil water storage capacity, and soil texture values balance aboveground and belowground resource partitioning while allowing the expression of seasonal drought (Coops and Waring 2011; Coops et al. 2011). Initial soil water availability was set at 50% of the overall soil water storage capacity. Mean solar radiation information was sourced from Hember et al. (2017), based on 1971–2000 data.

Monthly climate information for temperature (min, mean, max), precipitation, and frost days were obtained from ClimateBC version 7.50 (Wang et al. 2016; Mahony et al. 2022) for normal, dynamic, and future climates. ClimateBC is a software package that locally downscales historic and future climate data (800 m resolution) into scale-free point information for BC (Wang et al. 2016). Mean monthly climate data from the period 1961–1990 were used to represent normal climate conditions (Fig. 2), and historic monthly climate data from plot establishment to year 2023 were used to represent dynamic conditions (Fig. 2). Future monthly climate data from the years 2024 to 2100 reflect three Shared Socioeconomic Pathways (SSPs) under low (SSP1-2.6), medium (SSP2-4.5), and high (SSP5-8.5) climate change scenarios (Fig. 2). All SSPs represent the eight General Circulation Model (GCM) ensemble developed by Mahony et al. (2022) that aligns with the forcing scenarios used by the Intergovernmental Panel on Climate Change.

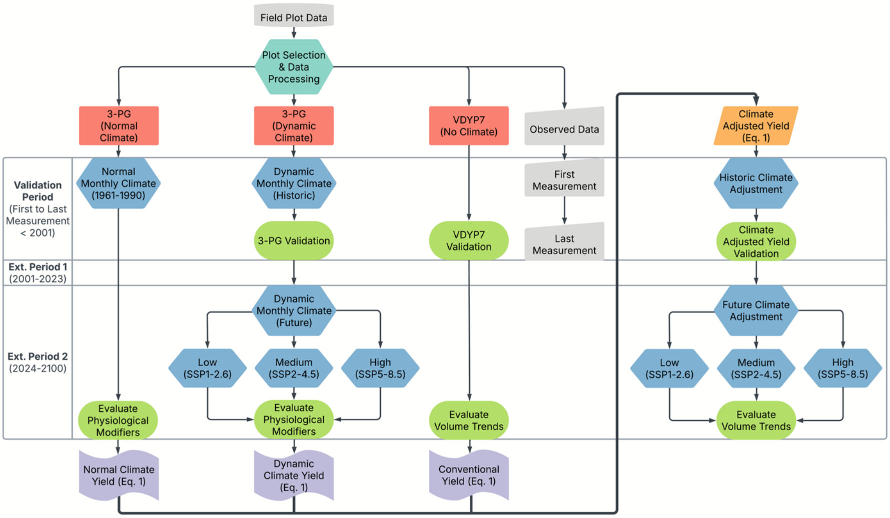

Fig. 2 Flow diagram of the approach used to evaluate VDYP7, 3-PG under a normal climate, 3-PG under a dynamic climate, and climate-adjusted yields based on Eq. 1. The validation and extended projection periods (Ext. Period 1, Ext. Period 2) are identified by gray boxes, including the climate assumptions used in each period

Field Plot Selection and Data Processing

Repeated measurement PSP data were used to initialize and validate 3-PG, VDYP7, and develop climate-adjusted yields. Field plots were selected from a publicly available dataset developed by the BC Ministry of Forests, Forest Analysis and Inventory Branch (BCMF-FAIB 2024). This dataset is a compilation of five plot networks across BC and includes measurements in young, old, and middle-aged stands. The PSP data were filtered to meet the input requirements of each model, limit confounding effects, and allow a fair model assessment. The selected plots occurred within the study area (Fig. 1), had no documented silvicultural treatments, and had a measurement interval of at least five years. Each plot contained trees that were large enough to support VDYP7 projections (Trees with a DBH ≥ 7.5 cm) and included measured stand ages and compiled dominant heights for the leading species. Each plot also included spatial coordinates to obtain essential information for 3-PG, specifically latitude, soil fertility, soil water storage capacity, solar radiation, and localized climate data. Neither 3-PG nor VDYP7 directly model layered stands, mixed-species stands, or major insect attack. As a result, old "veteran" trees were excluded from the analysis, and the selected plots occupied pure stands (≥ 80% basal area) of lodgepole pine, Douglas-fir, interior spruce, or subalpine fir. Furthermore, all PSP measurements occurred before 2001 to avoid severe mortality and lingering aftereffects from the 2000–2012 Mountain Pine Beetle (MPB; *Dendroctonus ponderosae*) epidemic (Alfaro et al. 2015; BCMFLNRO 2016; BCMFLNRORD 2018). After filtering, 856 plots were selected across the BC interior: 420 for lodgepole pine, 343 for Douglas-fir, 63 for subalpine fir, and 30 for interior spruce (Fig. 1). Plots meeting the above criteria came from BC's oldest PSP network and were established subjectively, using historic protocols without explicit random stratification or grid-based sampling.

Volume was calculated using provincial tree-level taper equations (Kozak 2004) and provincial mixed-effects models under the BCMF-FAIB (2024) compilation. Stem and foliage biomass were calculated using Canadian national tree-level equations, based on height and DBH (Ung et al. 2008). Root biomass was calculated using the plot-level softwood equation for the Carbon Budget Model of the Canadian Forest Sector (Kurz et al. 1996). Although the selected plots reflect pure stands of lodgepole pine, Douglas-fir, subalpine fir, and interior spruce, secondary species were sometimes present. Biomass from deciduous trees (e.g. *Populus*, *Larix occidentalis*) was excluded from 3-PG projections, and biomass from secondary evergreen species (e.g. *Pinus monticola*) was modeled as the plot's dominant species.

Modeling Approach

After plot selection and data processing, each plot was modeled using four approaches: (1) 3-PG under a normal monthly climate from 1961–1990; (2) 3-PG under a dynamic monthly climate; (3) VDYP7 without climate sensitivity; and (4) derived climate-adjusted yields based on Eq. 1 (Fig. 2). Projections for each approach were initialized at the first PSP measurement and modeled until the last

PSP measurement before 2001 (hereafter the end of the validation period). Given 3-PG's focus on evergreen forests (Landsberg and Waring 1997), 3-PG projections were initialized for the softwood evergreen component of each plot. VDYP7 projections were initialized using all stand components, including deciduous evergreen (e.g. *Larix occidentalis*) and deciduous hardwood trees (e.g. *Populus tremuloides*). Then, model performance was evaluated using observed growth from the repeated measurement dataset. 3-PG stem mass and volume were validated under a dynamic climate. VDYP7 volume was validated with no climate sensitivity, and climate-adjusted volume was validated based on the climate trends that were produced by Eq. 1 (Fig. 2). Next, all projections were continued through year 2100, and long-term trends were explored on the climate-adjusted yields and the 3-PG physiological modifiers. Dynamic 3-PG projections used historic climate data from model initialization through year 2023 and transitioned to future climate scenarios (low, medium, high) between the years 2024 and 2100 (Fig. 2).

Climate Adjusted Yields

Parallel projections of 3-PG under a normal climate, 3-PG under a dynamic climate, and VDYP7 with no climate sensitivity were modeled throughout the entire projection period (Fig. 2; first PSP measurement to year 2100). Then, climate-adjusted yields were developed for each plot based on 3-PG volume (Eq. 1).

$$CAY_{ijk} = Y_{ij}\left(\frac{VD_{ijk}}{VN_{ij}}\right) \tag{1}$$

where CAY is climate-adjusted yield (m^3/ha), Y is conventional yield from VDYP7 (m^3/ha), VD is volume from 3-PG under a dynamic climate (m^3/ha), VN is volume from 3-PG under a normal climate (m^3/ha), i is the plot, j is the index year, and k is the historic or future climate scenario that was applied to the dynamic 3-PG projection.

Model Validation

At the end of the validation period (Fig. 2), modeled predictions were compared to PSP observations using the simple statistics average model bias, relative model bias, and efficiency (Bokalo et al. 2013). Average Model Bias (AMB) is the mean residual error (Eq. 2). Relative Model Bias (RMB) expresses AMB as a percentage of the observed mean (Eq. 3), and Efficiency (EF) is a statistic similar to the coefficient of determination (r^2) (Eq. 4; Bokalo et al. 2013). 3-PG validation statistics and graphics for stem biomass and volume were developed based on the softwood evergreen component of each plot, and VDYP7 validation statistics and graphics for volume were developed based on all species.

$$AMB = \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)}{n} \tag{2}$$

$$RMB = \frac{AMB}{\overline{O}} \times 100 \tag{3}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{4}$$

where O_i are observed values derived from the PSP data, P_i are predicted values from 3-PG, VDYP7, or the model fusion, $\bar{O}$ is the observed mean value, and n is the total number of plots (Bokalo et al. 2013).

Graphics comparing predicted and observed values were also developed at the end of the validation period (Fig. 2), exploring detailed trends relative to a reference 1:1 line. In addition, residuals (observed-predicted values) from the end of the validation period (Fig. 2) were plotted against projection length to demonstrate model performance over time (Bokalo et al. 2013). Residual figures are located in the Supplementary Information. For all validation materials, observed PSP values included ingress (i.e. regeneration that did not meet or exceed the PSP measurement threshold at the beginning of the validation period; Dempster 2024).

Long-Term Trends

To demonstrate the model fusion approach and explore long-term growth trends, mean VDYP7 volume, climate-adjusted volume (Eq. 1), and climate-adjusted volume increment (Eq. 1) were plotted for each species between the years 2024 and 2100 using BEC zones and subzones (Meidinger and Pojar 1991) that represent a divergent moisture and temperature gradient. Climate-adjusted volumes and volume increments (Eq. 1) reflect the normal period from 1961–1990 and three future climate scenarios that represent low, medium, and high climate change (Fig. 2). Then, mean 3-PG physiological modifiers were plotted between the years 2024 and 2100 for each species and BEC selection (Fig. 2) under the same climate assumptions. The 3-PG physiological modifiers include spring temperature, spring frost, spring soil water availability, summer temperature, summer vapor pressure deficit, and summer soil water availability. Previous studies found these 3-PG modifiers important for identifying the distribution and vulnerability of lodgepole pine, Douglas-fir, subalpine fir, and spruce (Mathys et al. 2014, 2018).

The selected BEC zones (Meidinger and Pojar 1991) were ecologically dominated by the species of interest (e.g. Douglas-fir/IDF) and partitioned by subzone, representing relatively “dry” and “wet” sites. Lodgepole pine plots were selected from the SBPS zone in the dry/cold (dc) and moist/cool (mk) subzones, and Douglas-fir plots were chosen from the IDF zone in the very dry/very hot (xx) and wet/warm (ww) subzones. Subalpine fir plots were identified from the

ESSF zone in the wet/mild (wm) and wet/cold (wc) subzones, and interior spruce plots were isolated from the SBS zone in the moist/warm (mw) and very wet/cool (vk) subzones. Climatic and ecological details about these BEC zones and subzones can be found in Meidinger and Pojar (1991).

Results

3-PG Validation

3-PG stem biomass and volume produced generally balanced and unbiased trends relative to a 1:1 line (Fig. 3). Underpredictions of stem biomass and volume occurred near the maximum observed values for Douglas-fir and subalpine fir (Fig. 3). AMB values for interior spruce indicated a small stem biomass overprediction (−0.96 Mg/ha) and a small volume underprediction (3.59 m^3/ha). Lodgepole pine and subalpine fir AMB values were overpredicted for stem biomass (> -10 Mg/ha) and volume (> -12 m^3/ha). Meanwhile, Douglas-fir had larger AMB overpredictions of −23.73 Mg/ha for stem biomass and −37.43 m^3/ha for volume. RMB values were $> -15.27\%$ for Douglas fir and within ±8% for lodgepole pine, subalpine fir, and interior spruce. Stem biomass and volume EF values ranged from 0.48 to 0.58 for lodgepole pine, 0.76 to 0.78 for Douglas-fir, and 0.53 to 0.72 for interior spruce. Subalpine fir EF values were 0.76 for both stem biomass and volume (Fig. 3). Residual plots for stem biomass and volume indicated relatively constant variability over time for lodgepole pine and subalpine fir (Fig. S1). However, lodgepole pine stem biomass trended toward overprediction under the longest projection lengths. Douglas-fir residuals increased slightly over time. A relatively small sample size ($N=30$) hindered the interpretation of the interior spruce residuals (Fig. S1). All validation projections were designed to be a long as possible and included plots with a 43-year projection period for lodgepole pine, a 43-year projection period for Douglas-fir, a 20-year projection period for subalpine fir, and a 70-year projection period for interior spruce (Fig. S1). In most cases, 3-PG stem biomass and volume trends tracked each other (Fig. 3).

VDYP7 Validation

VDYP7 volume produced generally balanced and unbiased graphical trends relative to a 1:1 line for lodgepole pine, Douglas-fir, and interior spruce (Fig. 4). Subalpine fir was consistently underpredicted relative to a 1:1 line (Fig. 4), and Douglas-fir was underpredicted near the maximum observed values for the species (Fig. 4). AMB values for VDYP7 volume indicated an overprediction for lodgepole pine (−34.49 m^3/ha). Douglas-fir and interior spruce had volume underpredictions of 16.37 m^3/ha and 25.15 m^3/ha, respectively. Subalpine fir had a larger volume underprediction at 46.82 m^3/ha. RMB values for volume ranged

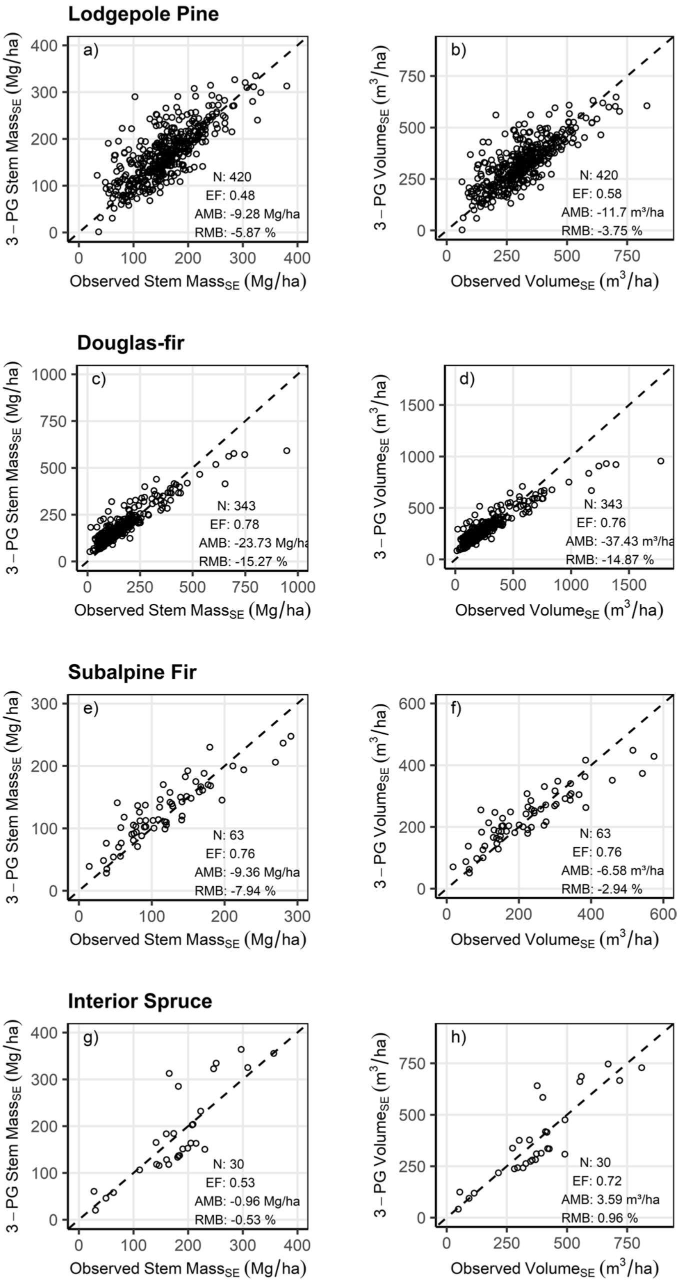

Fig. 3 3-PG stem mass predictions versus observed stem mass from the permanent sample plot dataset (**a**, **c**, **e**, **g**) at the end of the validation period (Fig. 2), and 3-PG volume predictions versus observed volume from the permanent sample plot dataset (**b**, **d**, **f**, **h**) at the end of the validation period (Fig. 2). In this figure, 3-PG was run using a dynamic monthly climate throughout the validation period. All values reflect the Softwood Evergreen (SE) component of each plot. Figures are plotted by species group. An exact fit is represented by a dashed 1:1 line. [Key: N = number of plots; EF = efficiency; AMB = average model bias; RMB = relative model bias]

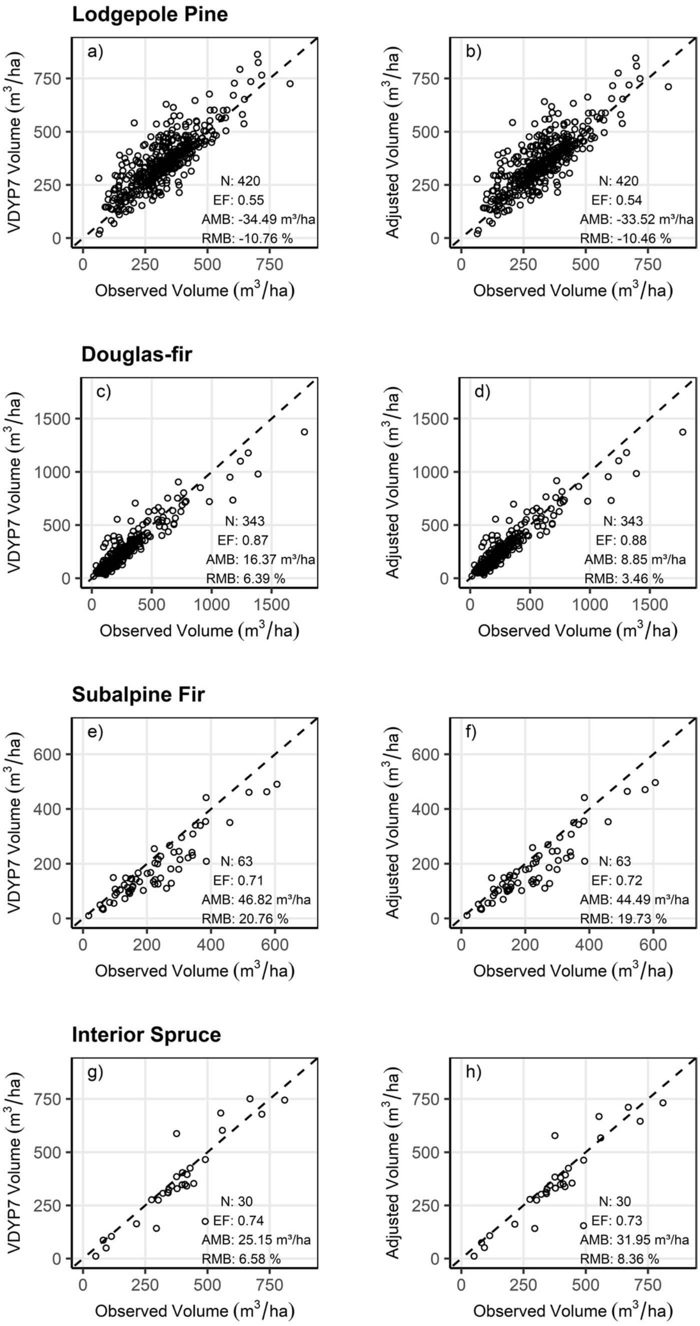

Fig. 4 VDYP7 volume predictions versus observed volume from the permanent sample plot dataset (**a**, **c**, **e**, **g**) at the end of the validation period (Fig. 2). Climate-adjusted volume predictions from Eq. 1 versus observed volume from the permanent sample plot dataset (**b**, **d**, **f**, **h**) at the end of the validation period (Fig. 2). Figures are plotted by species group. An exact fit is represented by a dashed 1:1 line. [Key: N = number of plots; EF = efficiency; AMB = average model bias; RMB = relative model bias]

from −10.76% to 6.58% for lodgepole pine, Douglas-fir, and interior spruce. RMB was 20.76% for subalpine fir volume. EF values for VDYP7 volume were 0.55 for lodgepole pine, 0.87 for Douglas-fir, 0.71 for subalpine fir, and 0.74 for interior spruce (Fig. 4). Residual plots for VDYP7 indicated relatively constant variability over time for lodgepole pine with a slight overprediction under long projection lengths (Fig. S2). Douglas-fir residuals also increased slightly, and VDYP7 residuals for subalpine fir exhibited a consistent underprediction over time. A relatively small sample size (N = 30) hindered the interpretation of the interior spruce residuals (Fig. S2). VDYP7 validation projections were designed to be as long as possible and match the projection lengths of 3-PG (Fig. S2).

Climate-Adjusted Yield Curves

Climate-adjusted yields validated similarly to VDYP7 over the historic growth period, producing generally balanced and unbiased graphical trends relative to a 1:1 line for lodgepole pine, Douglas-fir, and interior spruce (Fig. 4). Subalpine fir was consistently underpredicted relative to a 1:1 line (Fig. 4), and Douglas-fir was underpredicted near the maximum observed values for the species (Fig. 4). AMB values for climate-adjusted volume indicated an overprediction for lodgepole pine (−33.52 m^3/ha) and underpredictions for Douglas-fir (8.85 m^3/ha) and interior spruce (8.36 m^3/ha). Subalpine fir had a larger AMB value for climate-adjusted volume at 44.49 m^3/ha. RMB values for climate-adjusted volume ranged from −10.46% to 3.46% for lodgepole pine, Douglas-fir, and interior spruce. RMB was 19.73% for climate-adjusted subalpine fir volume. EF values for climate-adjusted volume were 0.54 for lodgepole pine, 0.88 for Douglas-fir, 0.72 for subalpine fir, and 0.73 for interior spruce (Fig. 4). Residual plots for climate-adjusted yield displayed relatively constant variability over time for lodgepole pine (Fig. S2), and Douglas-fir residuals for climate-adjusted yield increased slightly over time. Subalpine fir residuals for climate-adjusted yield also reflected a consistent underprediction over time. A relatively small sample size (N = 30) hindered the interpretation of the interior spruce residuals for climate-adjusted yield (Fig. S2).

Long-Term Trends

Climate-adjusted yields increased lodgepole pine volumes by about 1% for the SBPSdc plots and 2% for the SBPSmk plots in year 2100 across the low, medium, and high climate change scenarios (Fig. 5). Similarly, climate-adjusted volume increments for lodgepole pine were slightly elevated relative to baseline conditions. No climate change scenario produced exceptional volume increments for lodgepole pine. Douglas-fir volumes on dry IDFxx plots increased by 5% under the low climate change scenario, 6% under the medium climate change

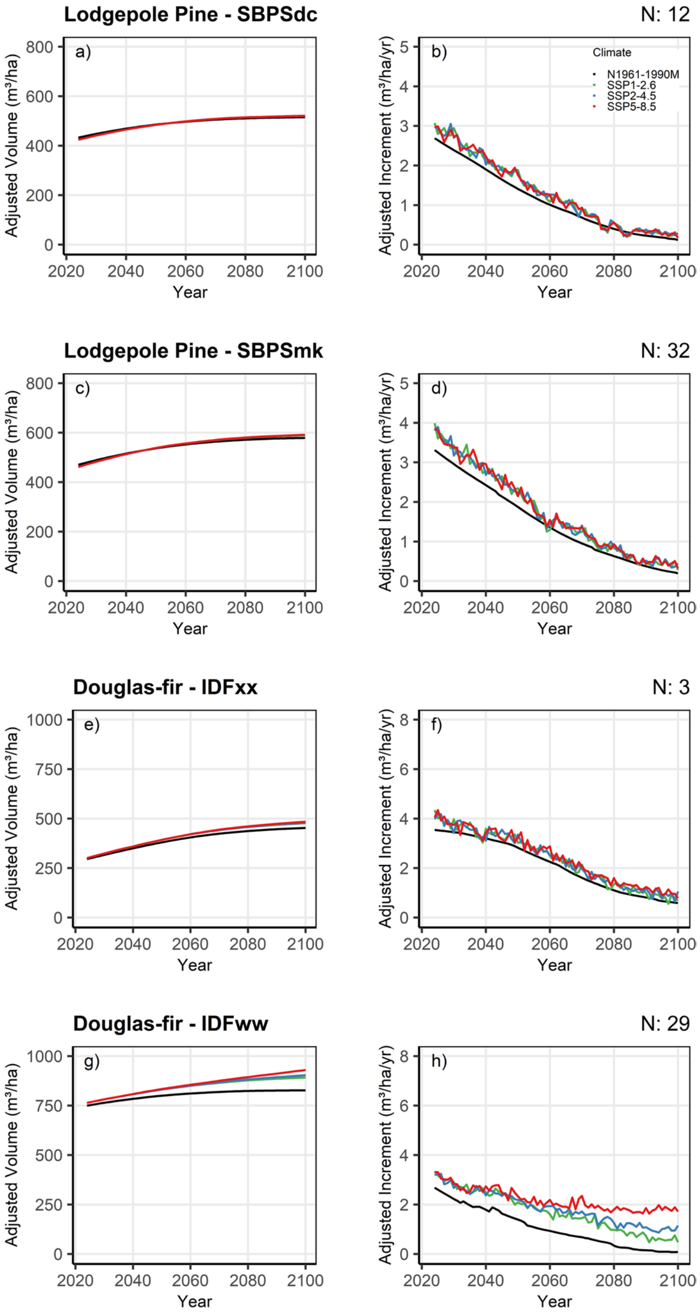

Fig. 5 Mean climate-adjusted volume (**a**, **c**, **e**, **g**) and volume increment (**b**, **d**, **f**, **h**) from Eq. 1 between the years 2024 and 2100 for lodgepole pine and Douglas-fir plots across a BEC moisture and temperature gradient. [Key: SBPS = Sub-Boreal Pine—Spruce; dc = dry/cold; mk = moist/cool; IDF = Interior Douglas-fir; xx = very dry/very hot; ww = wet/warm; N = number of plots; N1961-1990M = normal climate between 1961–1990; SSP1-2.6 = low climate change; SSP2-4.5 = medium climate change; SSP5-8.5 = high climate change]

scenario, and 7% under the high climate change scenario in year 2100. Douglas-fir volumes on wet IDFww plots increased by 8%, 9%, and 13% under the low, medium, and high climate change scenarios, respectively. Douglas-fir volume increments were slightly elevated on the IDFxx plots and increased noticeably under increasing climate change on the IDFww plots (Fig. 5). Subalpine fir volumes on wet/mild ESSFwm plots increased by 12% under the low climate change scenario, 14% under the medium climate change scenario, and 17% under the high climate change scenario in year 2100 (Fig. 6). Subalpine fir volume gains on wet/cold ESSFwc plots were exceptional with increases of 20%, 24%, and 31% under the low, medium, and high climate change scenarios. Subalpine fir volume increments were elevated across both subzones. However, climate change substantially increased climate-adjusted increments on ESSFwc plots (Fig. 6). Interior spruce achieved volume gains of 5%, 5%, and 4% on drier SBSmw plots in year 2100 under the low, medium, and high climate change scenarios, respectively. On very wet sites (SBSvk), interior spruce volumes increased by 21%, 23%, and 26% in year 2100. Similar to subalpine fir, climate-adjusted increments for interior spruce were elevated on SBSmw plots but were much larger on very wet SBSvk plots (Fig. 6).

3-PG's physiological modifiers help explain these climate-adjusted volume responses (Figs. 7 & S3-S5). Increasing climate change tended to enhance springtime growth and hinder summer growth, producing a combined effect that was negligible for lodgepole pine and very positive on wet Douglas-fir, subalpine fir, and interior spruce plots (Figs. 5 & 6). Combined growth impacts were less positive on increasingly dry Douglas-fir, subalpine fir, and interior spruce plots (Figs. 5 & 6). Relative to normal climate conditions (1961–1990), all of the selected lodgepole pine, Douglas-fir, subalpine fir, and interior spruce plots experienced improved springtime temperatures and fewer frost-prone days under increasing climate change (Figs. 7 & S3-S5). Springtime water availability also remained favorable on the lodgepole pine, subalpine fir, interior spruce, and wet Douglas-fir plots (Figs. 7 & S3-S5). However, very dry Douglas-fir plots experienced declining springtime water availability under increasing climate change (Fig. 7). Physiological modifier trends varied in the summer. All of the lodgepole pine, Douglas-fir, subalpine fir, and interior spruce plots saw a negative impact on summer vapor pressure deficits under increasing climate change (Figs. 7 & S3-S5). Lodgepole pine experienced increasing summer soil moisture stress under increasing climate change and unfavorable summer temperatures under extreme climate change (Fig. S3). Douglas-fir plots also faced improved summer temperatures that were offset by persistent summer droughts under climate change (Fig. 7). Subalpine fir and interior spruce plots benefited from positive summer temperatures and soil moisture conditions under climate change, with a slight moisture restriction on drier sites (Figs. S4 & S5). Interior spruce plots also experienced unfavorable summer temperatures under extreme climate change (Fig. S5).

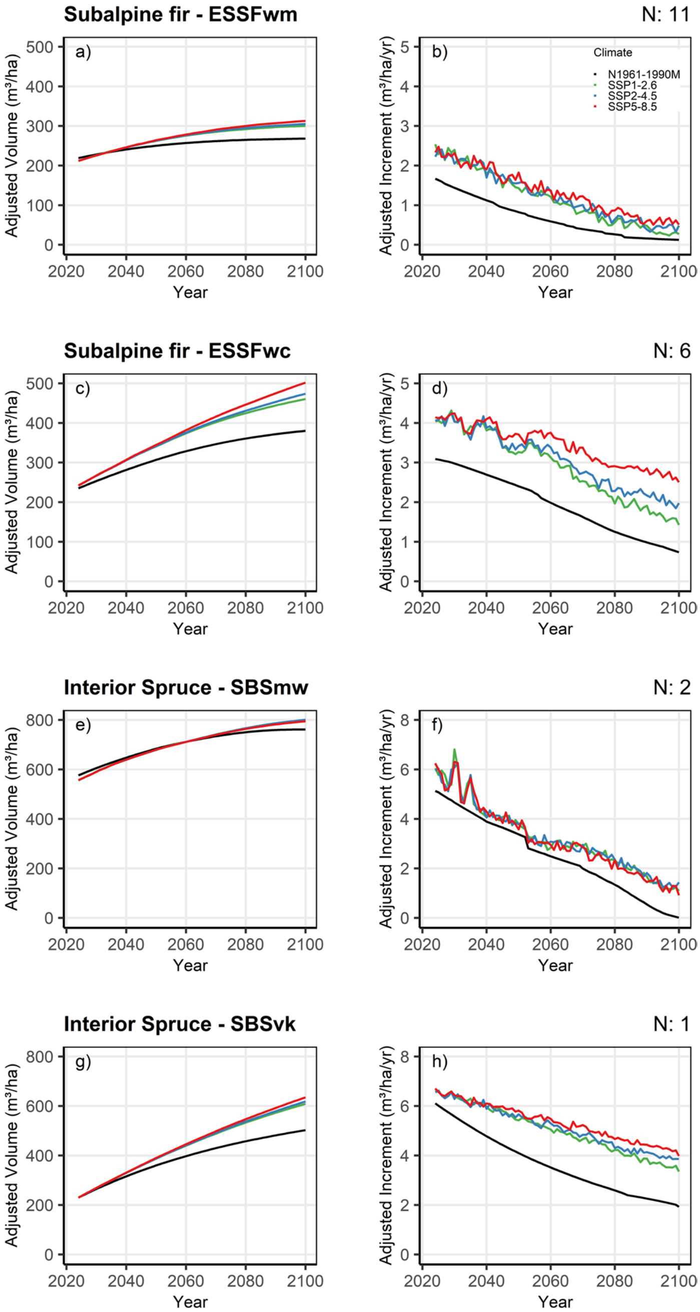

Fig. 6 Mean climate-adjusted volume (**a**, **c**, **e**, **g**) and volume increment (**b**, **d**, **f**, **h**) from Eq. 1 between the years 2024 and 2100 for subalpine fir and interior spruce plots across a BEC moisture and temperature gradient. [Key: ESSF = Engelmann Spruce—Subalpine Fir; wm = wet/mild; wc = wet/cold; SBS = Sub-Boreal Spruce; mw = moist/warm; vk = very wet/cool; N = number of plots; N1961-1990M = normal climate between 1961–1990; SSP1-2.6 = low climate change; SSP2-4.5 = medium climate change; SSP5-8.5 = high climate change]

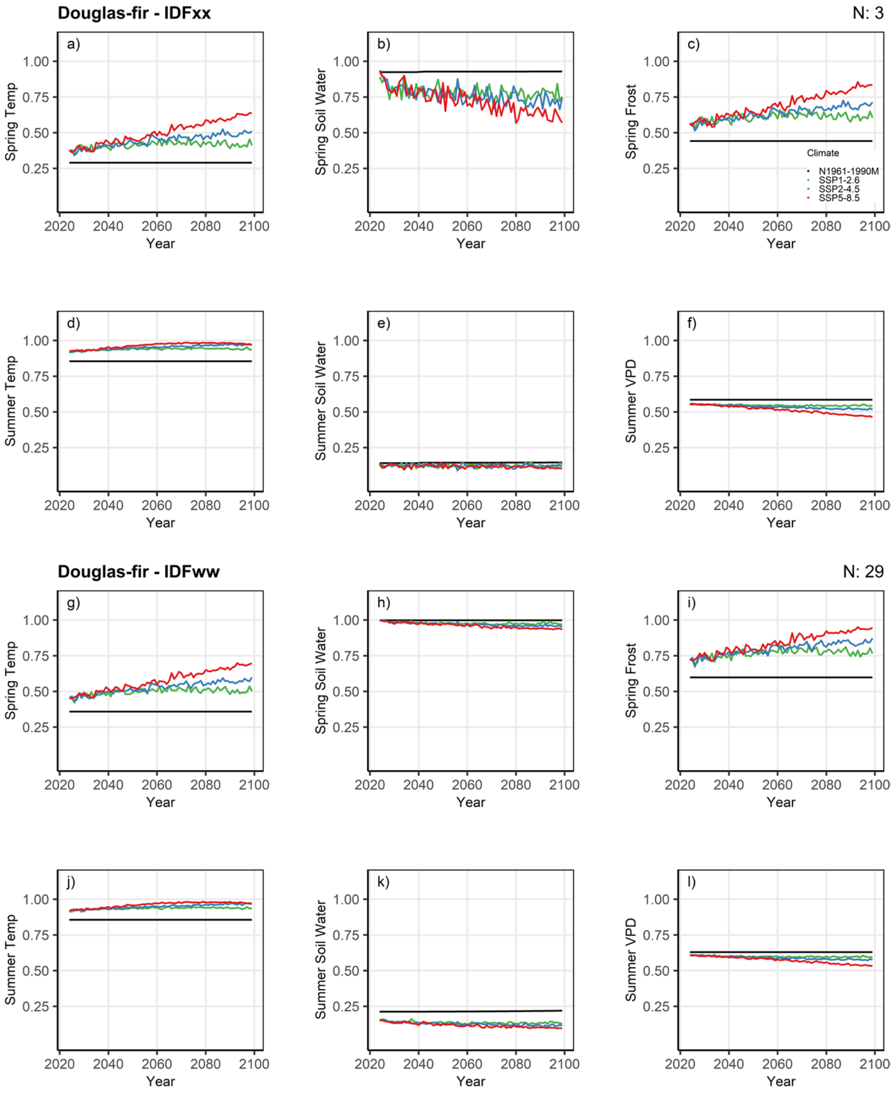

Fig. 7 Mean 3-PG physiological modifiers between the years 2024 and 2100 for Douglas-fir plots across a BEC moisture and temperature gradient. Interior Douglas-fir zone plots on very dry/very hot sites (IDFxx; **a**-**f**) and wet/warm sites (IDFww; **g**-**l**). Mean spring temperature (**a**, **g**), spring soil water (**b**, **h**), and spring frost modifiers (**c**, **i**). Mean summer temperature (**d**, **j**), summer soil water (**e**, **k**), and summer vapor pressure deficit modifiers (**f**, **l**). Physiological modifiers for additional BEC zones are located in the Supplementary Information. All modifiers are dimensionless. [Key: Temp = temperature; VPD = vapor pressure deficit; N = number of plots; N1961-1990M = normal climate between 1961–1990; SSP1-2.6 = low climate change; SSP2-4.5 = medium climate change; SSP5-8.5 = high climate change]

Discussion

In this study, we validated 3-PG on pure stands of lodgepole pine, Douglas-fir, subalpine fir, and interior spruce across the BC interior, demonstrating 3-PG's ability to predict stem mass and volume over extended periods (Figs. 3 & S1). While direct comparisons between 3-PG and VDYP7 were not the intent of this study, validated volumes from 3-PG were qualitatively similar to validated volumes from VDYP7, based on graphical and statistical measures (Figs. 3 & 4). The growth similarities between 3-PG and VDYP7 are encouraging and may suggest that 3-PG could be used to develop yield curves directly, provided additional evaluation and calibration. For our deployment of 3-PG, many of the computing and data limitations historically associated with hybrid and process-based models (e.g. Landsberg 2003; Weiskittel et al. 2011) were less acute, given modern computing hardware and a rich ecosystem of supporting models, software, and data products. For example, Canadian national biomass equations (Kurz et al. 1996; Ung et al. 2008), r3PG's open-source coding (Trotsiuk et al. 2020), and the availability of high-quality climate and environmental data (Wang et al. 2016; Coops et al. 2012; Hember et al. 2017; Mahony et al. 2022) made 3-PG relatively straightforward to implement using traditional inventory information. In addition, a thorough and publicly available PSP dataset (BCMF-FAIB 2024) significantly aided our analysis. We also developed climate-adjusted yields by fusing the climate sensitive, hybrid/process-based growth model 3-PG with the conventional growth model VDYP7. Climate-adjusted yields validated similarly to VDYP7 (Fig. 4). This similarity is likely caused by strong model performance by 3-PG (Figs. 3 & S1), strong model performance by VDYP7 (Figs. 4 & S2), and VDYP7's extensive calibration using BC field plot data (Government of British Columbia 2023).

For the selected plots on a moisture and temperature gradient, climate-adjusted yields provided small volume uplifts for lodgepole pine (1–2%) and moderate volume uplifts on drier Douglas-fir (5–7%) and interior spruce (4–5%) plots (Figs. 5 & 6). Larger volume uplifts occurred on wetter Douglas-fir (8–13%), subalpine fir (12–31%), and interior spruce (21–26%) plots (Figs. 5 & 6). Under climate change, future climates in the montane cordillera are likely to include increased mean annual precipitation, increased mean annual temperatures, extended growing periods, and additional frost-free days (Wotherspoon et al. 2023). While these climate conditions are potentially favorable and may improve growth on wetter plots, seasonal climate interactions moderated climate-adjusted growth on drier plots (Figs. 5–7 & S3-S5). Improved springtime temperatures and fewer frosts were often offset by unfavorable vapor pressure deficits in the summer (Figs. 7 & S3-S5). Climate-adjusted yields for subalpine fir improved noticeably under increasing climate change. Subalpine fir sites are generally cold and frost-limited (e.g. Mathys et al. 2018) and appear to benefit most from a warming climate. However, improved growing conditions in subalpine forests may encourage species composition shifts that are detrimental to subalpine fir (Mathys et al. 2017). Lodgepole pine and Douglas-fir plots also experienced persistent and increasing summer droughts under climate change, offsetting spring gains and improved summer temperatures (Figs. 7 & S3). Persistent and increasingly droughty conditions are likely to encourage additional damaging agents (e.g. insects) and may have a negative impact on lodgepole pine, Douglas-fir, and other species (Mathys et al. 2017; Levesque and Hamann 2022).

In order to avoid confounding effects from the 2000–2012 MPB epidemic (Alfaro et al. 2015; BCMFLNRO 2016; BCMFLNRORD 2018), we relied on an older PSP dataset to validate 3-PG, explore climate-adjusted yields, and demonstrate our model fusion approach. These older PSPs were established using subjective plot locations (Penner 2021) that likely favored high quality, timber-productive sites. As a result, marginal, droughty, or otherwise vulnerable sites may have been underrepresented in our analysis. Caution needs to be used when interpreting the climate implications of this study or applying our climate responses at larger scales. For example, Lafond et al. (2024) developed climate-adjusted yields curves for landscape-level biogeoclimatic zones near Smithers, BC using the LANDIS-II Forest Carbon Succession extension. Their approach produced a variety of climate-adjusted outcomes, ranging from small yield increases to large yield reductions. When these climate-adjusted yields were applied across a diverse landscape with productive and unproductive biogeoclimatic zones, the cumulative effect reduced long-term sustained yield, unless supplemented by silvicultural treatments (Lafond et al. 2024).

Predicting forest growth is a challenging task, and the modeling approach used in this study is not without limitations. For example, we explored past and future growth on relatively pure stands. Encouraging mixed-species stands has been identified as a critical climate change adaptation measure to increase resistance to insect attacks and drought (Barbeito et al. 2021; Comeau 2021). Additional research is needed to explore climate effects on stands with complex, multi-cohort structures. We also explored growth on only four commercial tree species. Approximately 26 tree species exist in BC (Meidinger and Pojar 1991), and all of these tree species would benefit from an exploration of growth under climate change. Neither 3-PG nor VDYP7 directly model disturbances like wildfire or MPB, competition between stand-level cohorts, or genetic impacts on forest growth (Landsberg and Waring 1997; Penner 2021). 3-PG's growth projections also rely on density-dependent mortality (Sands and Landsberg 2002) and do not consider background mortality due to drought (Liu et al. 2021) or species vulnerability (Crookston et al. 2010). The version of 3-PG used in this study (Landsberg and Waring 1997) also does not consider changing CO_2 concentrations in the atmosphere that can impact growth (Weiskittel et al. 2011). Calibrating 3-PG for additional tree species in BC, and/or localizing multi-cohort versions of 3-PG_{mix} (Forrester et al. 2021a) could be pursued. Additional analysis exploring managed stands or unfavorable sites would also be useful, since variable site-level responses are likely under climate change (Moreau et al. 2022; MacKenzie and Mahony 2021). Exploring juvenile sites may be of particular interest, given the potential for different growth responses from mature and recently regenerated trees (Huang et al. 2004; Mathys et al. 2018).

Nevertheless, our model fusion approach shows promise under validation and demonstrates plausible long-term responses across a range of species, sites, and climate scenarios. We envision this framework supporting landscape-level models that include climate sensitive growth, timber supply decision-making, and carbon accounting (e.g. Hof et al. 2017; Brecka et al. 2020; Lafond et al. 2024; Quebec Chief Forester 2020). 3-PG's ability to run at a variety of scales using conventional and satellite-based inventory products (e.g. Mathys et al. 2018; Forrester et al. 2021b; du Toit et al. 2024) make it an attractive choice for the immediate exploration of climate sensitive growth in western Canada. By using 3-PG, our approach can also draw upon 3-PG's physiological modifiers to assess site-level climate vulnerability and help implement climate-informed management, identifying sites for targeted thinning or climate-informed transitions to more resilient species. This modeling framework could also be applied to multi-model ensembles that explore long-term growth under climate change (e.g. Boulanger et al. 2022) and the uncertainty related to these predictions (Metsaranta et al. 2024).

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Author Contributions Conceptualization: KMJ, NCC; Methodology: KMJ, NCC, AA, VCG, IB; Data Curation: KMJ; Analysis: KMJ; Visualization: KMJ; Supervision: NCC; Project Administration: NCC, AA; Funding Acquisition: AA, NCC; Writing—Original Draft Preparation: KMJ, NCC; Writing—Review and Editing: KMJ, NCC, AA, VCG, IB.

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Data Availability Please see the references for r3PG (Trotsiuk et al. 2020, 2023), VDYP7 (Government of British Columbia 2023), ClimateBC (Wang et al. 2016), and the BC PSP dataset (BCMF-FAIB 2024) for model/data download links and additional documentation. Additional data supporting this study are available from the corresponding author upon reasonable request.

Declarations

Competing Interests The authors declare no competing interests related to this work.

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