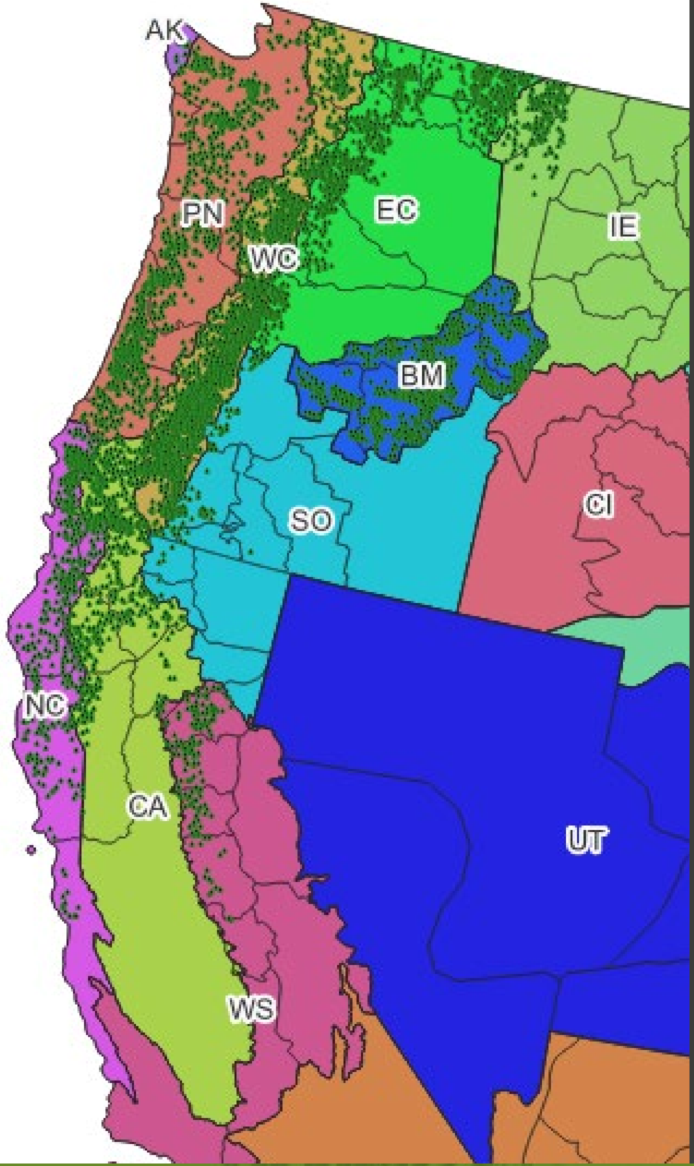


Integrating FIA with a new approach to make FVS climate-aware in the Pacific Northwest

David D. Diaz and Gregory J. Ettl

FIA Science Stakeholder Meeting
Nov 16, 2022

School of Environmental and Forest Sciences
Center for Sustainable Forestry at Pack Forest

Ecotrust

MOTIVATION

Why refit FVS (+ climate)?

- FVS calibration out of the box substantially differs from observed patterns in FIA or generally trusted yield curves.

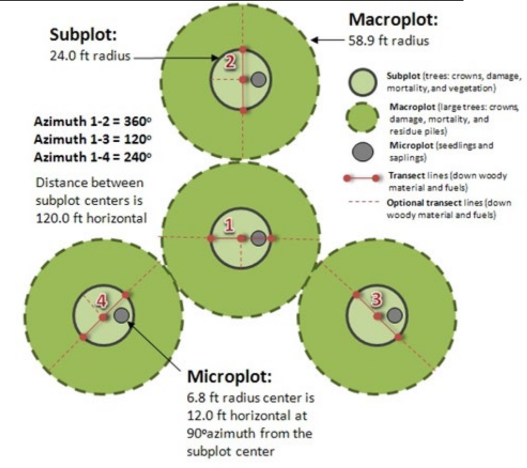
- Historically, FVS was fit to data from individual regions or locations, using a periodic (5- or 10-year) timestep.

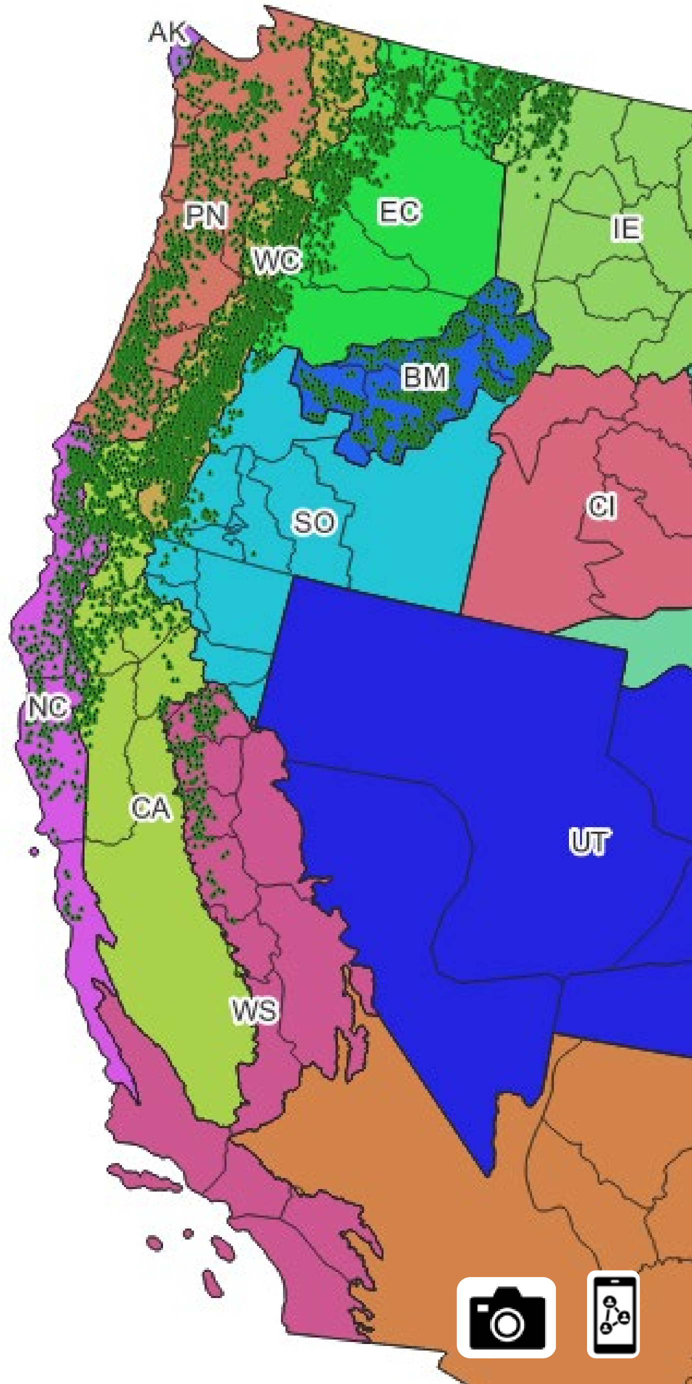
- The FIA provides a comparatively large and ongoing data stream with the type of information needed to calibrate FVS.

- Climate-FVS is not credible. Climatic multipliers for growth and mortality should be based on data for growth and mortality.

- The primary influences of climate on tree growth and mortality are expected at intervals shorter than 5- or 10-years (e.g., daily, monthly, or seasonally).

- We expect emergent climate effects at the edge of species ranges and want to learn from them to extrapolate better into future climates.





How FVS estimates diameter growth

$$\mathrm{BAI} = f(\mathrm{SIZE}, \mathrm{SITE}, \mathrm{COMP})$$
$$\mathrm{BAI} \sim \mathrm{DBH}^2_{t+1} - \mathrm{DBH}^2_t$$
$$\mathrm{DDS} = \mathrm{DIB}^2_{t+1} - \mathrm{DIB}^2_t \quad \ldots \; (\mathrm{DIB}_t = a_1 * \mathrm{DBH}_t^{a2})$$

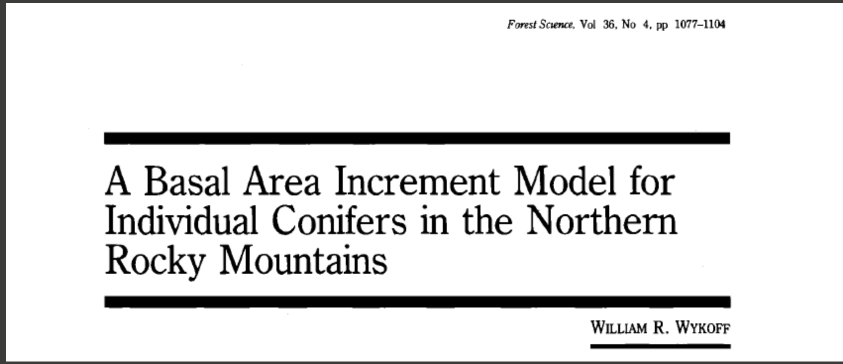
$$\mathrm{SIZE} = b_0 + b_1 * \ln(\mathrm{DBH}) + b_2 * \mathrm{DBH}^2$$
$$\mathrm{SITE} = b_3 * \ln(\mathrm{SI}) + b_4 * \mathrm{SL} + b_5 * \mathrm{EL} + \varepsilon_{\mathrm{LOC}}$$
$$\mathrm{COMP} = b_6 * \mathrm{CR} + b_7 * \mathrm{COMP}_{\mathrm{TREE}} + b_8 * \mathrm{COMP}_{\mathrm{STAND}}$$

added random effects

$$\mathrm{DDS} = \exp(\mathrm{SIZE} + \mathrm{SITE} + \mathrm{COMP}) + \varepsilon_{\mathrm{TREE}}$$
$$= e^{\mathrm{SIZE}} * e^{\mathrm{SITE}} * e^{\mathrm{COMP}}$$

effects are multipliers of growth

Where:
BAI is basal area increment; DDS is diameter difference squared; DBH is diameter at breast height; HAB and LOC are random effects for habitat type and ecoregion; SL is slope; EL is elevation; COMP is the combined effects indicating a tree's competitive environment; CR is crown ratio; $\mathrm{COMP}_{\mathrm{STAND}}$ is a stand-level competitive indicator (e.g., crown competition factor); and $\mathrm{COMP}_{\mathrm{TREE}}$ is a tree-level indicator of competitive status (e.g., basal area of larger trees).


Forest Science, Vol 36, No 4, pp 1077–1104

A Basal Area Increment Model for Individual Conifers in the Northern Rocky Mountains

William R. Wykoff


United States Department of Agriculture

Forest Service

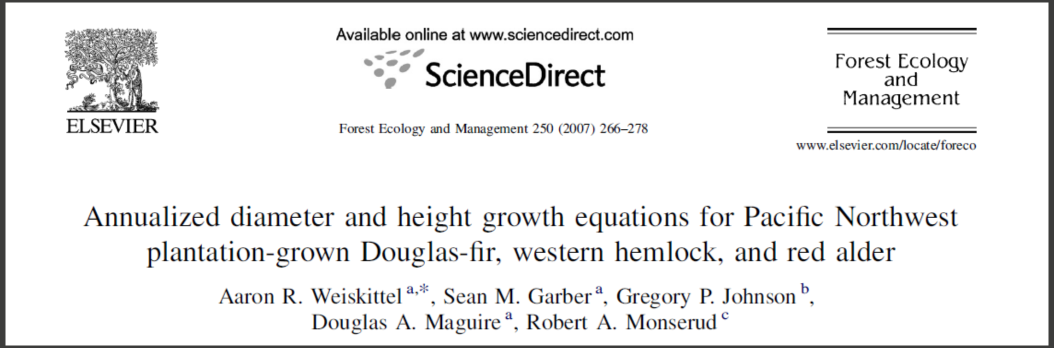
Forest Management Service Center

Fort Collins, CO

Pacific Northwest Coast (PN) Variant Overview

Forest Vegetation Simulator

Mixed effects modeling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Forest Ecology and Management
Forest Ecology and Management 250 (2007) 266–278
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Annualized diameter and height growth equations for Pacific Northwest plantation-grown Douglas-fir, western hemlock, and red alder

Aaron R. Weiskittel [a,*], Sean M. Garber [a], Gregory P. Johnson [b], Douglas A. Maguire [a], Robert A. Monserud [c]

$$DG = f(SIZE, SITE, COMP)$$

$$SIZE = b_1 * \ln(DBH) + b_2 * DBH^2 + b_3 * (UCR + 0.2)/1.2$$

$$SITE = b_0 + \varepsilon_{INST} + \varepsilon_{PLOT} + b_4 * \ln(SI - 1.37)$$

$$COMP = b_5 * COMP_{TREE} + b_6 * COMP_{STAND}$$

random effects added

$$DG = \exp(SIZE + SITE + COMP) + \varepsilon_{TREE}$$

Where:
DG_{OB} is outside-bark diameter growth; DBH is diameter at breast height; INST and PLOT and random effects for installation and plot; SI is Site Index, COMP is the combined effects indicating a tree's competitive environment; UCR is uncompacted crown ratio; $COMP_{STAND}$ is a stand-level competitive indicator (e.g., square root of stand basal area); and $COMP_{TREE}$ is a tree-level indicator of competitive status (e.g., basal area of larger trees divided by ln(DBH+5.0)).

Annualizing growth from periodic measurements

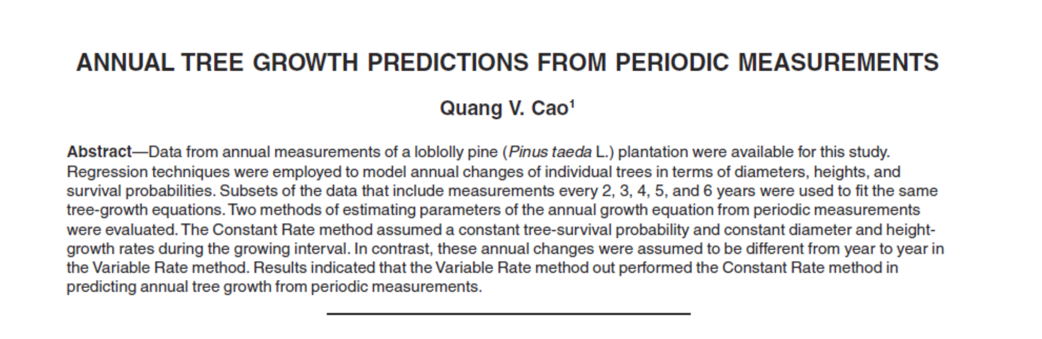
$$DG = f(SIZE, SITE, COMP)$$

$$SIZE = b_1*\ln(DBH) + b_2*DBH^2 + b_3*(UCR + 0.2)/1.2$$

$$SITE = b_0 + \varepsilon_{INST} + \varepsilon_{PLOT} + b_4*\ln(SI-1.37)$$ ← fix these params

$$COMP = b_5*COMP_{TREE} + b_6*COMP_{STAND}$$

$$DG = \exp(SIZE + SITE + COMP) + \varepsilon_{TREE}$$



ANNUAL TREE GROWTH PREDICTIONS FROM PERIODIC MEASUREMENTS

Quang V. Cao[1]

Abstract—Data from annual measurements of a loblolly pine (*Pinus taeda* L.) plantation were available for this study. Regression techniques were employed to model annual changes of individual trees in terms of diameters, heights, and survival probabilities. Subsets of the data that include measurements every 2, 3, 4, 5, and 6 years were used to fit the same tree-growth equations. Two methods of estimating parameters of the annual growth equation from periodic measurements were evaluated. The Constant Rate method assumed a constant tree-survival probability and constant diameter and height-growth rates during the growing interval. In contrast, these annual changes were assumed to be different from year to year in the Variable Rate method. Results indicated that the Variable Rate method out performed the Constant Rate method in predicting annual tree growth from periodic measurements.

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Annualizing growth from periodic measurements

$$DG = f(SIZE,\ SITE,\ COMP)$$

$$SIZE = b_1{*}\ln(DBH) + b_2{*}DBH^2 + b_3{*}(UCR + 0.2)/1.2 \quad \leftarrow \text{linear interp.}$$

$$SITE = b_0 + \varepsilon_{INST} + \varepsilon_{PLOT} + b_4{*}\ln(SI-1.37)$$

$$COMP = b_5{*}COMP_{TREE} + b_6{*}COMP_{STAND} \quad \leftarrow \text{linear interp.}$$

$$DG = \exp(SIZE + SITE + COMP) + \varepsilon_{TREE}$$

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Annualizing growth from periodic measurements

$$DG = f(SIZE, SITE, COMP)$$

← recursively update

$$SIZE = b_1 * \ln(DBH) + b_2 * DBH^2 + b_3 * (UCR + 0.2)/1.2$$

$$SITE = b_0 + \varepsilon_{INST} + \varepsilon_{PLOT} + b_4 * \ln(SI - 1.37)$$

$$COMP = b_5 * COMP_{TREE} + b_6 * COMP_{STAND}$$

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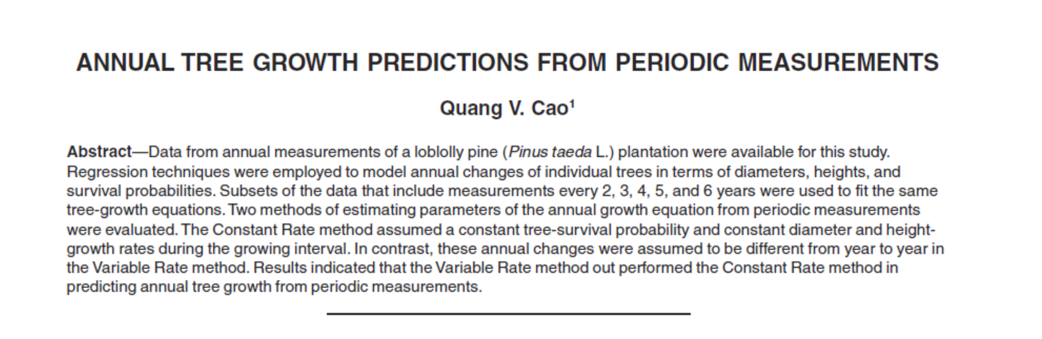
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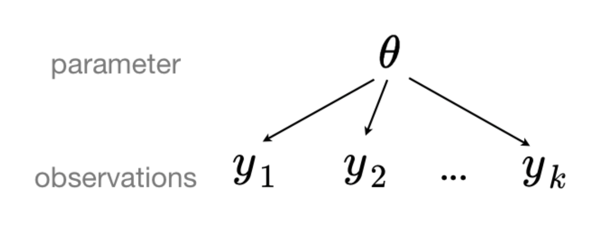
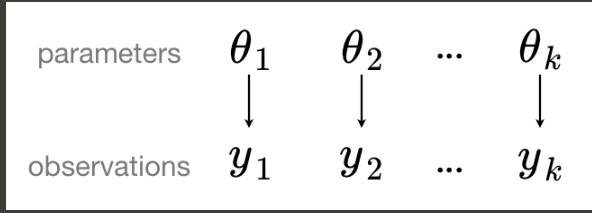
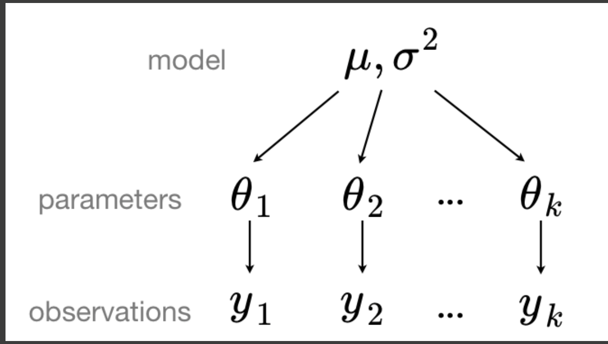
Learning to borrow strength



FULLY POOLED
Single set of model parameters (θ) is fit to observations across all ecoregions



UNPOOLED / INDEPENDENT REGIONS
Independent sets of model parameters (θ) are fit in each ecoregion to observations only from that ecoregion



HIERARCHICAL / PARTIAL POOLED
Model parameters in each ecoregion are constrained to follow a parent distribution shared across ecoregions.

Image credit: widdowquinn
https://github.com/widdowquinn/Teaching-Stan-Hierarchical-Modelling/tree/master/images

Incorporating climatic multipliers

$$\mathrm{BAI} \sim \exp(\mathrm{SIZE} + \mathrm{SITE} + \mathrm{COMP} + \mathrm{CLIM})$$
$$\mathrm{BAI} \sim e^{\mathrm{SIZE}} * e^{\mathrm{SITE}} * e^{\mathrm{COMP}} * e^{\mathrm{CLIM}}$$

Using an FVS keyword, we can drop in a climatic multiplier at runtime:

- $e^{\mathrm{CLIM}} = \mathrm{BAIMULT}$

- By refitting Base-FVS equations with climatic multipliers, updated Base-FVS equations can be hardcoded in FVS's Fortran source code, and climatic modifiers of growth (and mortality) can be applied at every cycle, allowing for alternative climatic impacts to be simulated.
- The simultaneous fitting of climatic modifiers alongside Base-FVS equations also ensures that the climatic drivers do exactly what they're fitted for (in contrast with existing Climate-FVS approaches based on presence/absence).

Drawing physiological inspiration

Two different physiologically-inspired models for predicting diameter growth following the potential * modifier approach with monthly climate drivers. Potential growth is driven by incident radiation and limited by climatic and edaphic constraints.

- **Physiological Processes Predicting Growth (3PG)**
  Described by Landsberg and Waring (1997), Landsberg and Sands (2016) and numerous other articles. A gap-scale model that predicts gross primary productivity as a function of monthly light, evaporative demand, soil water availability, temperature, and frost free days.

- **Vaganov-Shaskin Lite (VS-Lite)**
  Described by Tolwinski-Ward et al. (2011, 2013). This is a tree ring model that predicts ring width index (% annual change of a detrended ring width timeseries) as a function of monthly light, water, and temperature.

BAIMULT (3PG)

Nonlinear functions for soil moisture, temperature.

$$GPP = f(LIGHT, EVAP, WATER, TEMP, FFD)$$
$$GPP = (GHI*0.5 * \min(F_{VPD}, F_{WATER}) * F_{FFD}) * 0.03 * F_{TEMP}$$
$$F_{VPD} = \exp(-2.5*VPD)$$
$$F_{FFD} = 1 - (FFD / \text{total days per month})$$
$$F_{WATER} = 1 / (1 + (1- r)/c)^{n})$$
$$F_{TEMP} = ((T_{AVE}-T_{MIN})/(T_{OPT}-T_{MIN}))*((T_{MAX}-T_{AVE})/(T_{MAX}-T_{OPT}))** ((T_{MAX} - T_{OPT}) / (T_{OPT} - T_{MIN})) \text{ clipped to } [0, 1]$$

$$BAIMULT = b*GPP$$

Where: GPP is monthly gross primary production; GHI is incoming radiation; F_{VPD}, F_{FFD}, F_{TEMP}, and F_{WATER}, are factors constrained from [0,1] which reflect the impact of evaporative demand (VPD), frost inhibition (FFD), temperature effects on photosynthetic efficiency (TEMP) and soil moisture availability (WATER). r is soil moisture content, and c and n are coefficients that govern a sigmoid response function for F_{WATER}. T_{AVE} is monthly average temperature, while T_{MIN}, T_{OPT}, and T_{MAX} are parameters that produce a quadratic response function for F_{TEMP}.

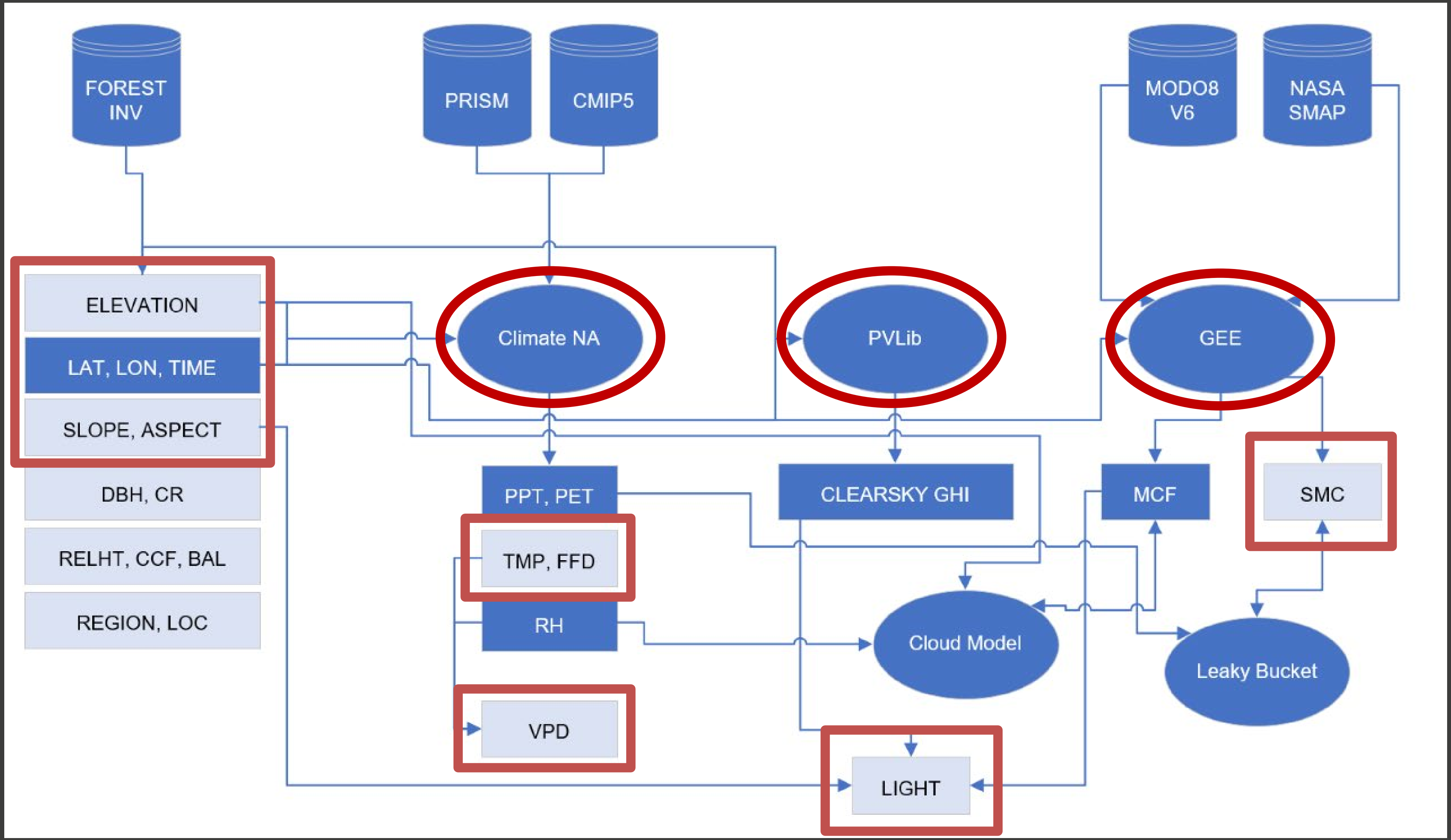
BAIMULT (VS-Lite)

Ramp functions for temperature and moisture.

$$F_L = GHI / GHI_{SS}$$
$$F_M = (M-M_1)/(M_2-M_1) \text{ clipped to } [0, 1]$$
$$F_T = (T-T_1)/(T_2-T_1) \text{ clipped to } [0, 1]$$
$$BAIMULT = F_L*\min(F_M, F_T)$$

Where: G is monthly ring width index summed to produce an annual ring width index; GHI is monthly incident radiation; GHI_{SS} is radiation in the summer solstice month; F_M and F_T are linear functions constrained from [0,1] which reflect lower limits on tree growth for temperature (T_1) or moisture (M_1) as well as thresholds above which growth is not limited by temperature (T_2) or moisture (M_2).

CLIMATIC DRIVERS: GETTING THE DATA



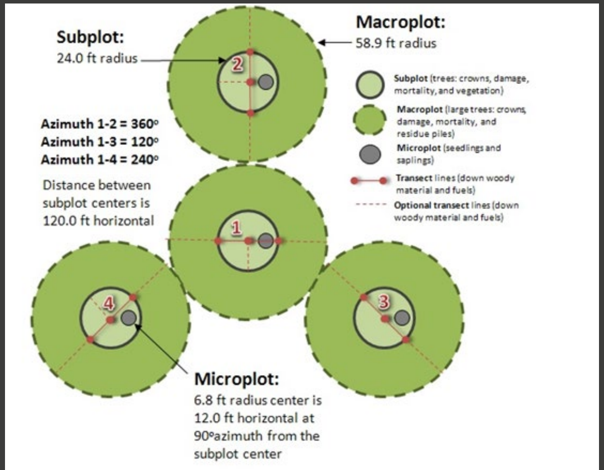
- Climatic data drawn from several publicly-available sources and open-source programs.
- We use this pipeline to generate monthly time series of cloud-adjusted radiation (LIGHT), soil moisture content (SMC), temperature (TMP), vapor pressure deficit (VPD), and frost free days (FFD).

AVAILABLE DATA

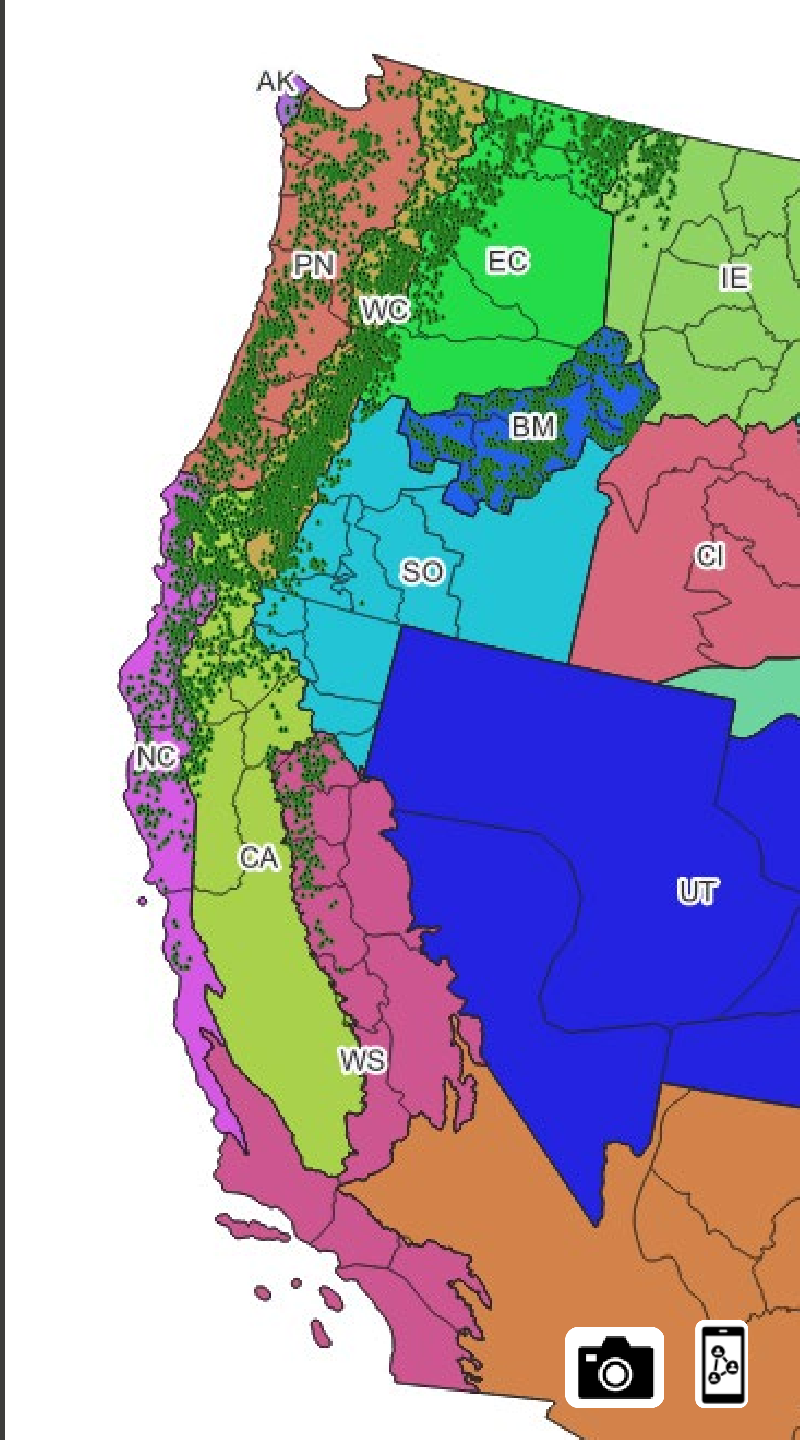
Repeatedly measured (FIA) plots

First pass model-fitting using Douglas-fir trees on FIA plots measured at 10 year interval across Washington, Oregon, or California.

Plots with fire, harvesting, or geologic disturbance were excluded.



REGION	# PLOTS	# TREES
Blue Mountains (BM)	835	3,575
Inland California (CA)	493	3,809
East Cascades (EC)	808	6,059
Inland Empire	154	882
Northern California (NC)	486	4,065
Pacific Coast (PN)	904	10,534
Southern Oregon (SO)	89	323
West Cascades (WC)	1,630	16,442
Western Sierra (WS)	153	951
TOTAL	5,552	46,440



Shift to POT*MOD implemented in Python

Adapted Wykoff Model to a Potential * Modifier form by:

- Transforming predictor variables such that increasing magnitude should correspond to decreasing growth (e.g., Site Index changed to 250/SI, Crown Ratio changed to 1 – CR)

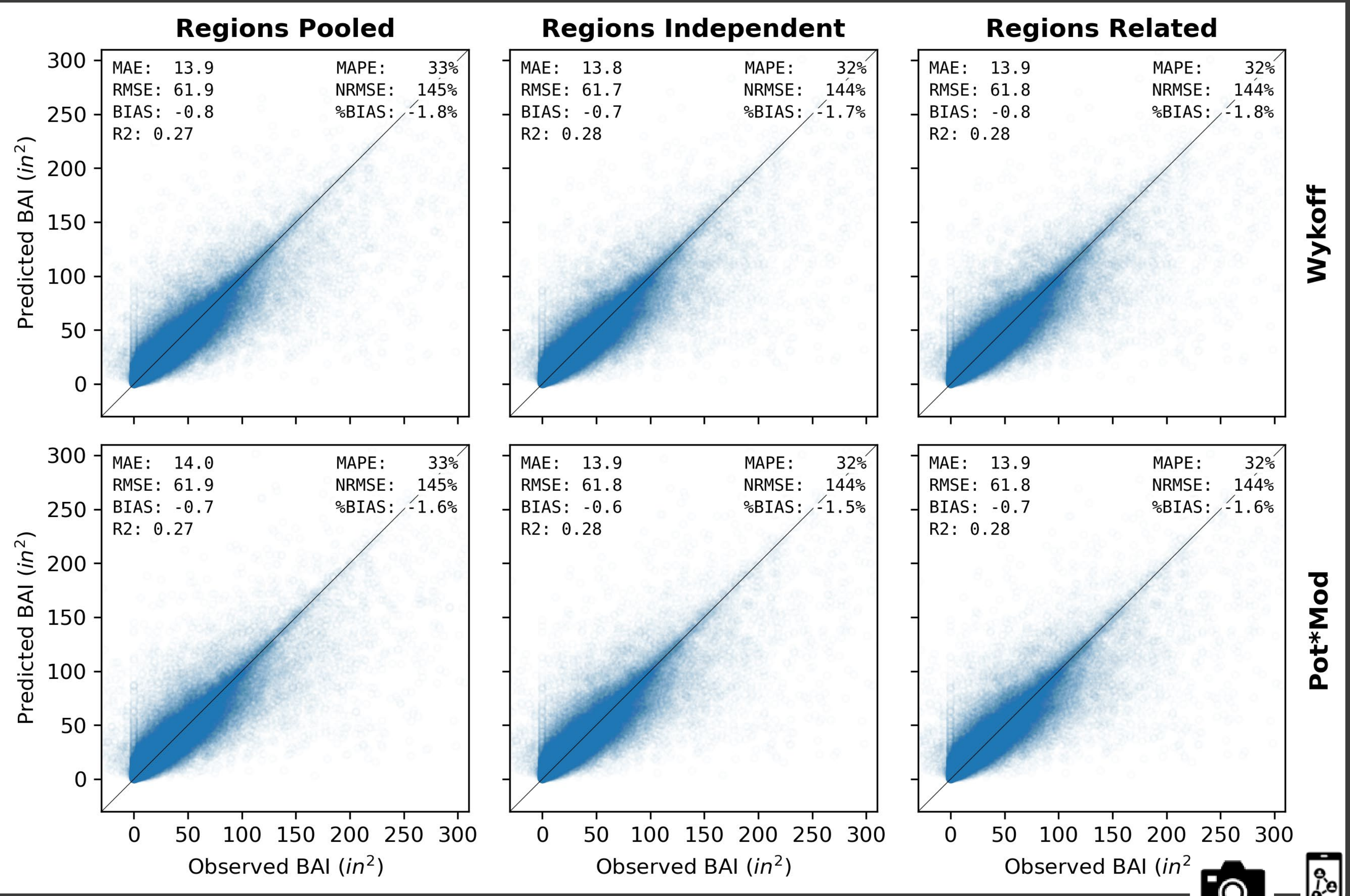
- Constrained coefficients for all variables except SIZE and random effects to be negative (resulting in multipliers < 1.0 when exponentiated). This precludes variables like SLOPE, ELEV, and COMP from positively influencing growth, and forces SIZE + random effects to predict maximum/potential incremental growth.

Adopted Bayesian model fitting using Numpyro.

- Employed Stochastic Variational Inference to fit models against data, rather than MCMC on full dataset.
- Guide for optimization seeks posterior mode for each parameter (Maximum A Posteriori)
- Leverages GPU and providing good performance so far.

Successfully fitting annualized equations with hierarchy

- Decent amount of variation explained with existing model (DG ~ 55% >> BAI ~ 28%)
- Partial pooling competitive with other model forms, expected to be more informative with climatic drivers
- Potential * Modifier form competitive with original Wykoff model form



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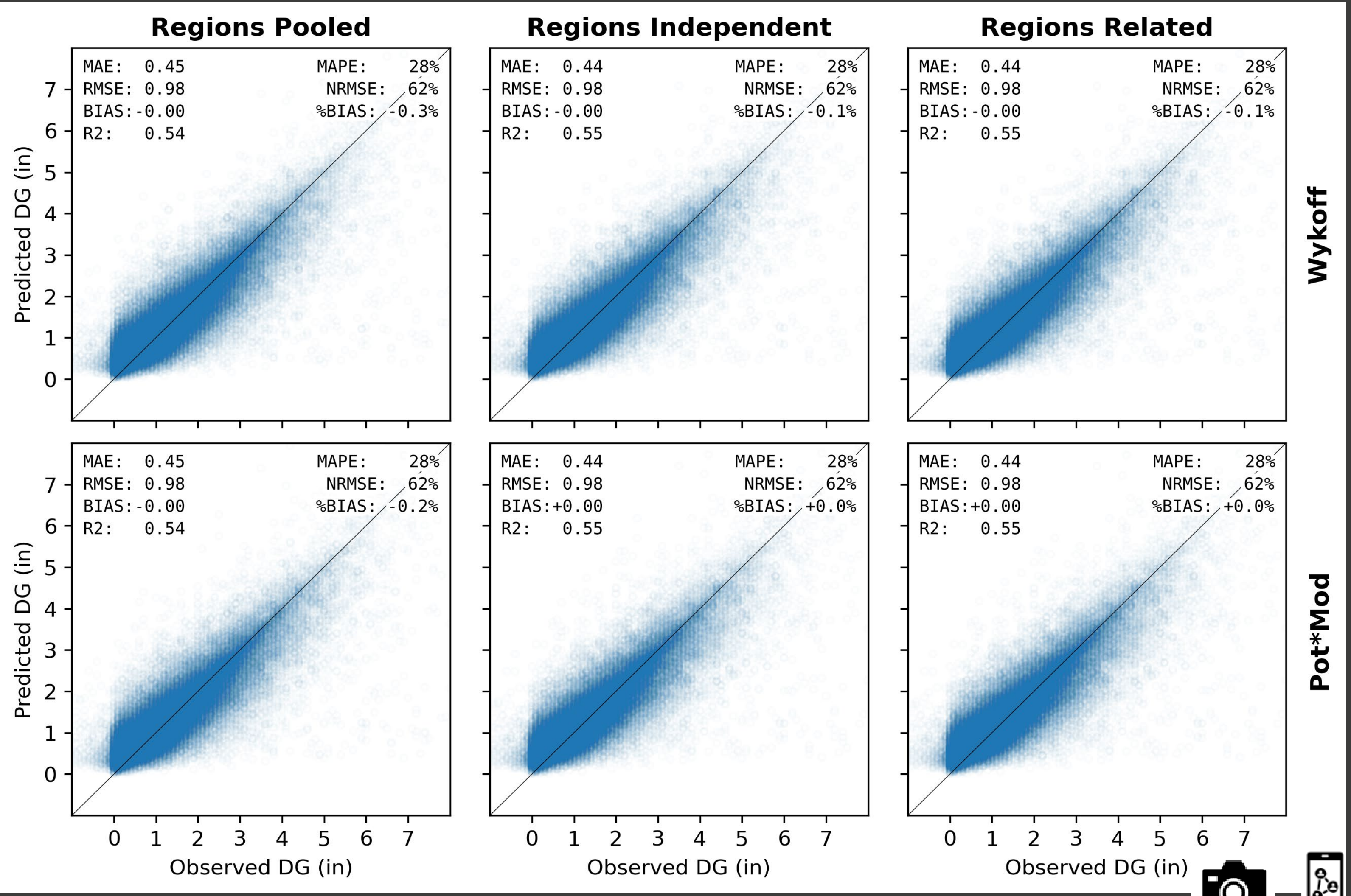
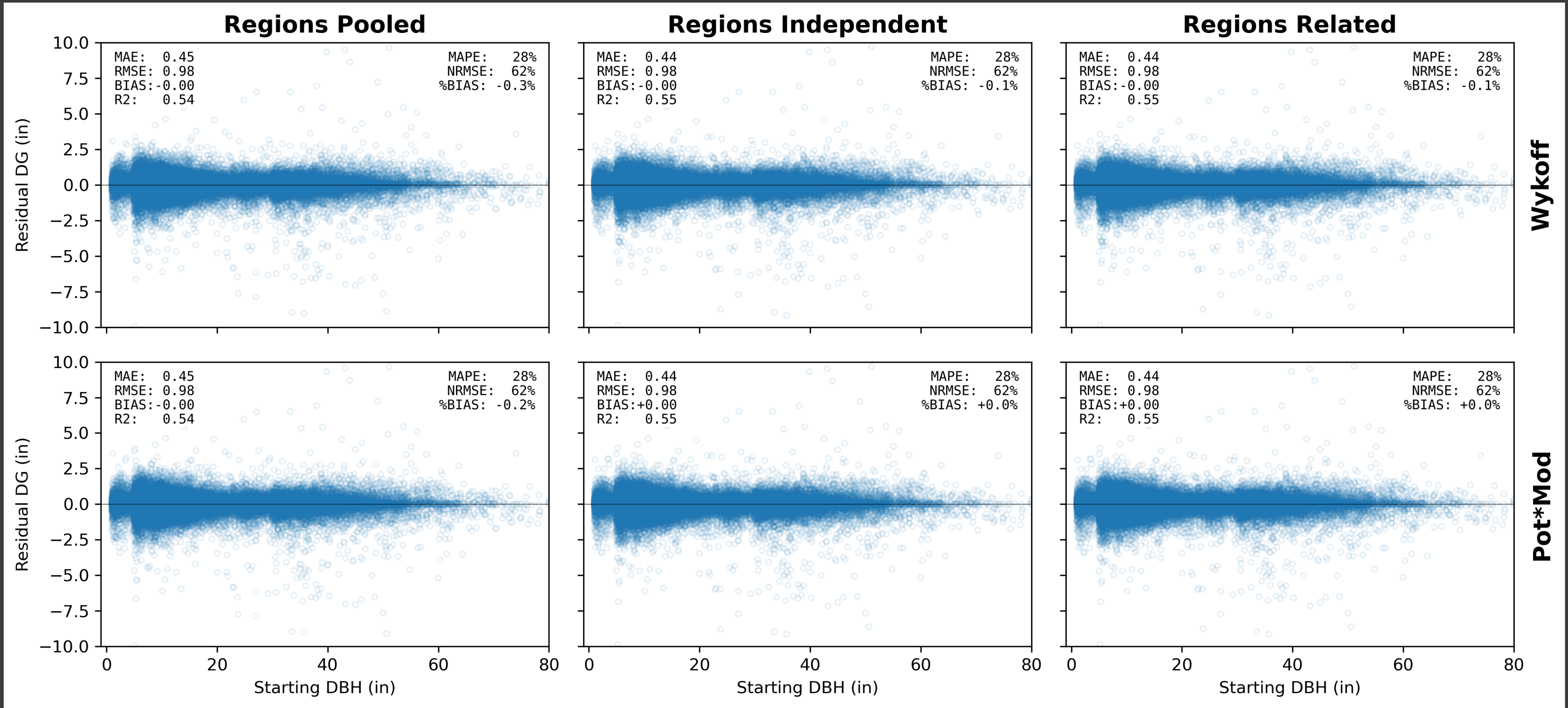


Homogenous variance and no clear trend in bias

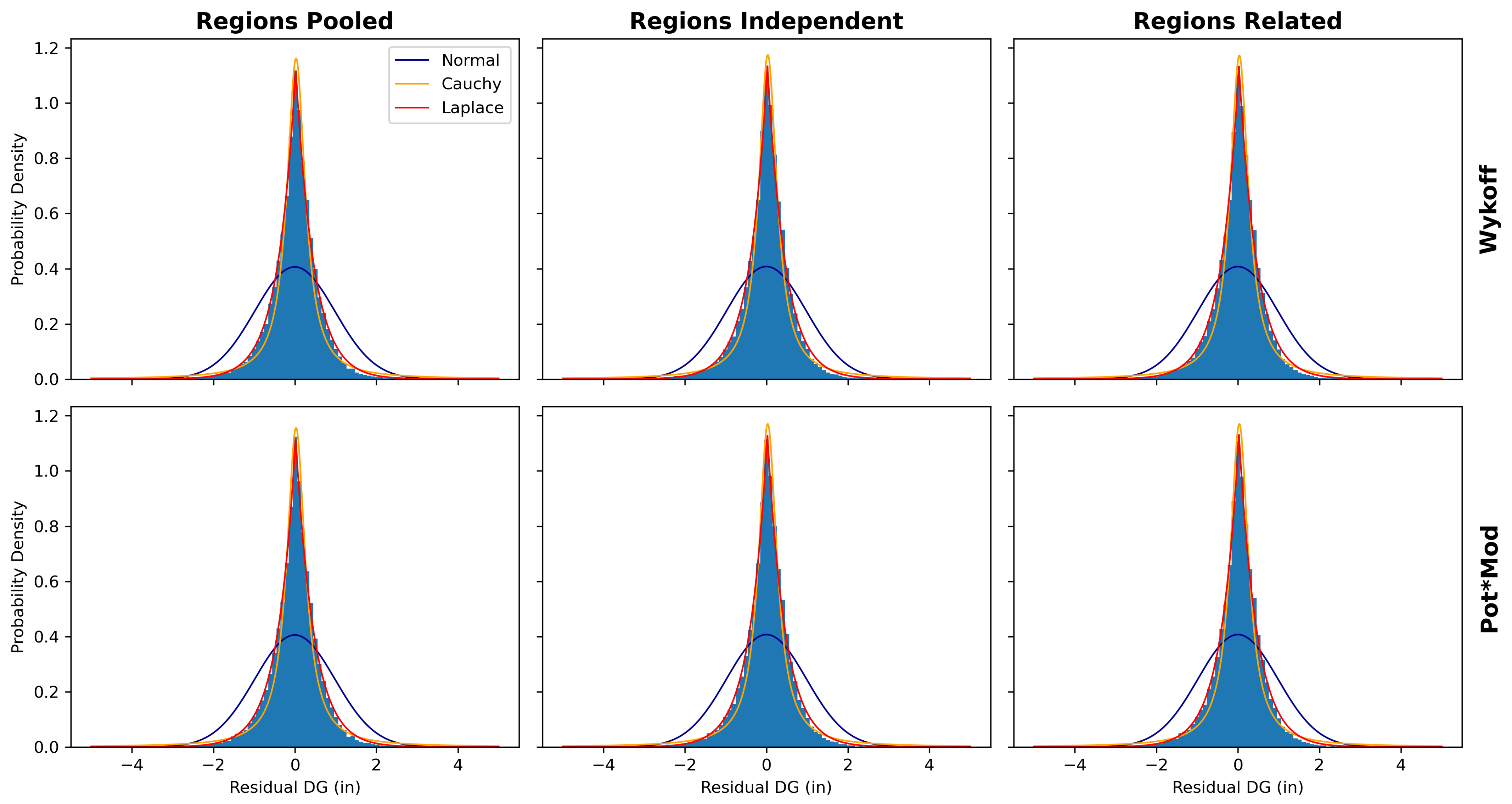
- Residuals vary consistently across the range of tree size



Fat tails

- Residuals for both BAI and DG are closer to Cauchy or Laplace than Normal.

- Laplace in theory would be a good choice if we believe DG is exponentially distributed.



Thank you.

https://github.com/d-diaz/refit_fvs