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Short Communication

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Spatial Variation in Dominant Height and Basal Area Development in a Coast Redwood Forest: Implications for Inventory and Modeling

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Abstract

We studied spatial autocorrelation in productivity across 110 ha of coast redwood (*Sequoia sempervirens*) forest in north coastal California. Height growth of dominant redwood trees, basal area (BA) growth, and volume growth were assessed in a grid of 234 permanent sample plots. Semi-variance analysis indicated that productivity was spatially autocorrelated yet variable at smaller spatial scales (i.e., between nearby sample plots). Dominant redwood height growth lacked spatial continuity beyond 200 m, indicating that estimates of site index from plots closer than 200 m would be spatially autocorrelated. BA development was spatially autocorrelated in plots up to 300 m apart within the study area characterized by heterogeneous topography and variable species composition. These findings suggest that estimates of redwood site index demand greater sampling intensity than sampling to index BA or volume productivity. Our analysis provides a framework for refining estimates of forest growth, yield, and carbon stocks in natural forests in accordance with divergent gradients of productivity.

Keywords

Growth and yield; Forest productivity; Semi-variance; *Sequoia sempervirens*; Site quality; Spatial autocorrelation

Introduction

Forest carbon stocks and growth vary in space and over time [1]. Land managers that are aware of spatial variations in forest growth and carbon can design appropriate inventories for forest data and adjust management accordingly. Forest inventory often involves systematic sampling along transect lines or within a network of permanent plots [2]. If these plots are too close together, data collected in neighboring sample plots can be spatially autocorrelated (covariance). This intensity of sampling is unnecessary and may lead to population variance being underestimated and sample precision over estimated due to lack of independence between samples [3-5].

Forest inventory data are often used to estimate stand basal area (BA) and volume per unit area, tree size attributes, and site quality. Site index (SI) is a proxy for forest site quality that is used to account for variation in productivity between stands. It is calculated by averaging height of dominant trees at an index age (i.e., areas with taller trees for a given age are expected to produce more wood volume per unit area). Forest production can be determined via repeat inventories or predicted using growth and yield models. These models commonly use SI to modify growth predictions. However SI does not fully explain variations in volume growth, especially in coast redwood (*Sequoia sempervirens* (D. Don) Endl.) stand [6-8].

Coast redwood is highly productive on good sites and may require different management strategies in accordance with different site qualities [9,10]. Redwood can tolerate shade, but its growth slows in accordance with its social position within stands [11-14]. Thinning enhances redwood tree diameter growth but response differs according to tree and crown size, social position, and site quality [8,15,16]. Consequently, redwood tree taper can be affected by management or disturbance and varies independent of SI, leading to different rates and patterns of growth. This plasticity of growth habit presents challenges for modelers of forest growth and yield, especially in multiaged stands where SI no longer applies. Berrill and O'Hara (2014) proposed a productivity index for even-aged and multiaged stands that indexes basal area increment (BAI) or volume increment (VI) of the overstory [8]. The *BAI index* and *VI index* for coast redwood stands compare productivity of an overstory aged 50-80 years to an expected value for any stand density, for all species combined or by isolating the redwood component to mitigate confounding influences of species composition which varies spatially throughout mixed stands.

Spatial representations of forest productivity or its predictor variables are particularly useful when they completely cover the landscape [17]. The spatial interpolation technique Kriging can be used in ecological studies, including forest inventory, to generate predictions of some variable in space between measured sample points. Application of Kriging is appropriate when the variable of interest varies spatially without abrupt changes. The related technique of co-Kriging exploits corollary relationships between easily-obtainable data and more "costly" data for the variable of interest, generating spatially-explicit Kriging predictions using a dense network of sample points for the easily-obtainable variable (e.g., remotely-sensed aspect or elevation) and its empirical relationship to the variable of interest (e.g., forest productivity) [18]. Kriging relies on covariance models of spatial autocorrelation (termed semi-variograms, or sample variograms) that describe the spatial continuity and variability of measured variables in space.

We developed sample variograms to quantify the extent of spatial autocorrelation in various indices of productivity: SI, BAI index, and VI index [8]. Our objective was to quantify the spatial continuity (i.e., how productivity varies in space) of redwood forest productivity along horizontal (basal) and vertical (height) axes of variation across the study area. We hypothesized that productivity along each axis (basal, height) was spatially autocorrelated making it predictable over some distance but locally variable between microsites. Our findings support design of carbon inventories and forest inventory for growth and yield data.

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Methods

Study site

The Railroad Gulch study area (lat. 39°19'47", long. 123°41'50") is located on Jackson Demonstration State Forest, Mendocino County, north coastal California, USA. The Mediterranean climate has winter rain and cool, dry summers. Mean annual rainfall is approximately 1100 mm at Railroad Gulch, with most precipitation occurring between October and April. Coastal fog can extend inland at night to cover Railroad Gulch and supplements rainfall with fog drip. The area has complex, heterogeneous topography with steep slopes of all aspects. Soils are well-drained loams formed in material derived from sandstone. Redwood-dominated stands regenerated naturally after the old-growth redwood forest was removed from Railroad Gulch around 1920 [19]. Redwood was commonly mixed with coast Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco var. *menziesii*) and tanoak (*Notholithocarpus densiflorus* (Hook. & Arn.) Manos et al.) and occasionally grand fir (*Abies grandis* (Douglas) Lindley), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Pacific madrone (*Arbutus menziesii* Pursh), and red alder (*Alnus rubra* Bong.).

In 1982, different methods of transformation towards an uneven-aged condition were tested. The 110-ha study area was divided into 14 contiguous blocks including two uncut control blocks. Basal area was reduced by 20%-50% in 12 blocks by partial harvesting across the range of species and tree sizes. Cutting individual stems dispersed throughout a block was termed individual tree selection. Group selection created a series of small openings within a block. A third approach involved combining individual tree and group selection within a square 8.1 ha treatment block. These treatments enhanced variability in forest structure but should not have affected site quality. A total of 234 circular fixed-radius 0.04 ha plots were established on random-start grids aligned north–south in the 14 blocks, collectively sampling almost 10% of the 110 ha study area (Figure 1).

Tree and stand data

Diameter at 1.37 m breast height (DBH) of all trees >10 cm DBH was measured before harvesting in 1982, and re-measured in 1992 and 2002. Tree height was measured in 1992 and 2002. A generalized height-diameter regression gave tree height estimates for a few trees missing height data [20]. Tree stemwood volume was predicted from dbh and height using species-specific volume equations and coefficients for Jackson Demonstration State Forest [21,22]. Tree data were summarized to the hectare level, and summarized separately for redwood in each plot. Summing individual tree values for stand density index (SDI) gave SDI for each plot [23]. BAI was average annual BA growth per hectare between the first and last re-measurements (approx. 20 years; 1982-2002). VI was average annual volume growth per hectare between the middle and last measurement (approx. 10 years; 1992-2002). Bark-to-pith increment cores collected from four dominant or codominant redwood trees in/near each plot gave breast height age data for the overstory. The height and age data for these four redwood trees were used to estimate SI for each sample plot - defined as the average height of dominant trees at base age 50 years [24].

Basal area and volume productivity

We calculated productivity index values representing the rate of accumulation of stand BA and volume for the redwood component in each sample plot and for all species combined. In cases where dominant tree ages varied between plots, we fitted a BA growth model to our sample plot data and used the model to 'grow' stand BA data forward or backward to a common age (60 years). We separated the redwood component from all other species in the plot by calculating an estimate of growing space in terms of SDI occupied by redwood in each plot. The ratio of redwood SDI to total plot SDI gave proportion of plot area occupied by redwood. This redwood portion of plot area was used to calculate hectare-level summary data for redwood component BA, BAI, and VI [25]. Finally, we took the difference between the plot data and the 'expected' stand average for that plot's stand density which gave an index value >1 for plots with above-average productivity and <1 for below-average plots [8]. By comparing each plot's BA, BAI, and VI to the expected value for that particular plot's stand density we mitigated the confounding influence of density. For each sample plot at Railroad Gulch, we calculated values for five different productivity indices: pre-harvest age-60 stand BA index, post-harvest (1982-2002) stand BAI index and redwood component BAI index, and post-harvest (1992-2002) stand VI index and redwood component VI index.

Spatial autocorrelation

The spatial continuity of redwood productivity index estimates over the entire Railroad Gulch study area was determined by variogram analysis. Semi-variance defined as half the average squared difference between pairs of sample plot index values was calculated for redwood SI and the stand and redwood component productivity indices [18]. Spherical models were fitted to the final omni-directional variograms. The distance (x-axis value) at which variograms reached a plateau (range) indicated maximum extent of spatial continuity (i.e., there was no evidence of spatial autocorrelation in productivity estimates between plots further apart than the variogram range). The size of the y-intercept relative to the maximum semi-variance (sill; largest y-axis value) was indicative of sampling error and small-scale variability (nugget effect). For example, a relatively large nugget effect (i.e., large y-intercept close to the sill) is indicative of low spatial continuity, whereas a small nugget effect (i.e., y-intercept near zero) is indicative of high degrees of spatial continuity in the variable of interest at short distances [18]. A large nugget effect for sample plot productivity estimates would suggest variability between microsites: rates of biomass accumulation were highly variable over short distances such as between neighboring plots. Data were analyzed using SAS software [26].

Results

Plot data and productivity index values

The average age of four redwood SI trees in each plot ranged from 46 to 62 years. Prior to partial harvesting in 1982, stand BA at age 60 years averaged 79.6 m^2 ha^{-1} and ranged from 0.42 to 233.9 m^2 ha^{-1} in 234 plots. Post-harvest stand BAI averaged 1.22 m^2 ha^{-1} yr^{-1} and redwood component BAI averaged 1.18 m^2 ha^{-1} yr^{-1}. Stand VI averaged 19.5 m^3 ha^{-1} yr^{-1} and redwood component VI averaged 18.1 m^3 ha^{-1} yr^{-1}. Growth data and productivity index values varied widely among plots. One plot with 100% redwood had the maximum VI of 61 m^3 ha^{-1} yr^{-1}. Redwood SI ranged from 20.6 to 40.6 m at base age 50 years between plots [8]. A wide range of productivity index values for pre-harvest age-60 BA index and post-harvest BAI index and VI index was also observed: the 5th percentile of index values was 0.53 (i.e., almost 50% below average) and the 95th percentile was 1.66 (i.e., 66% greater productivity than the average for any density).

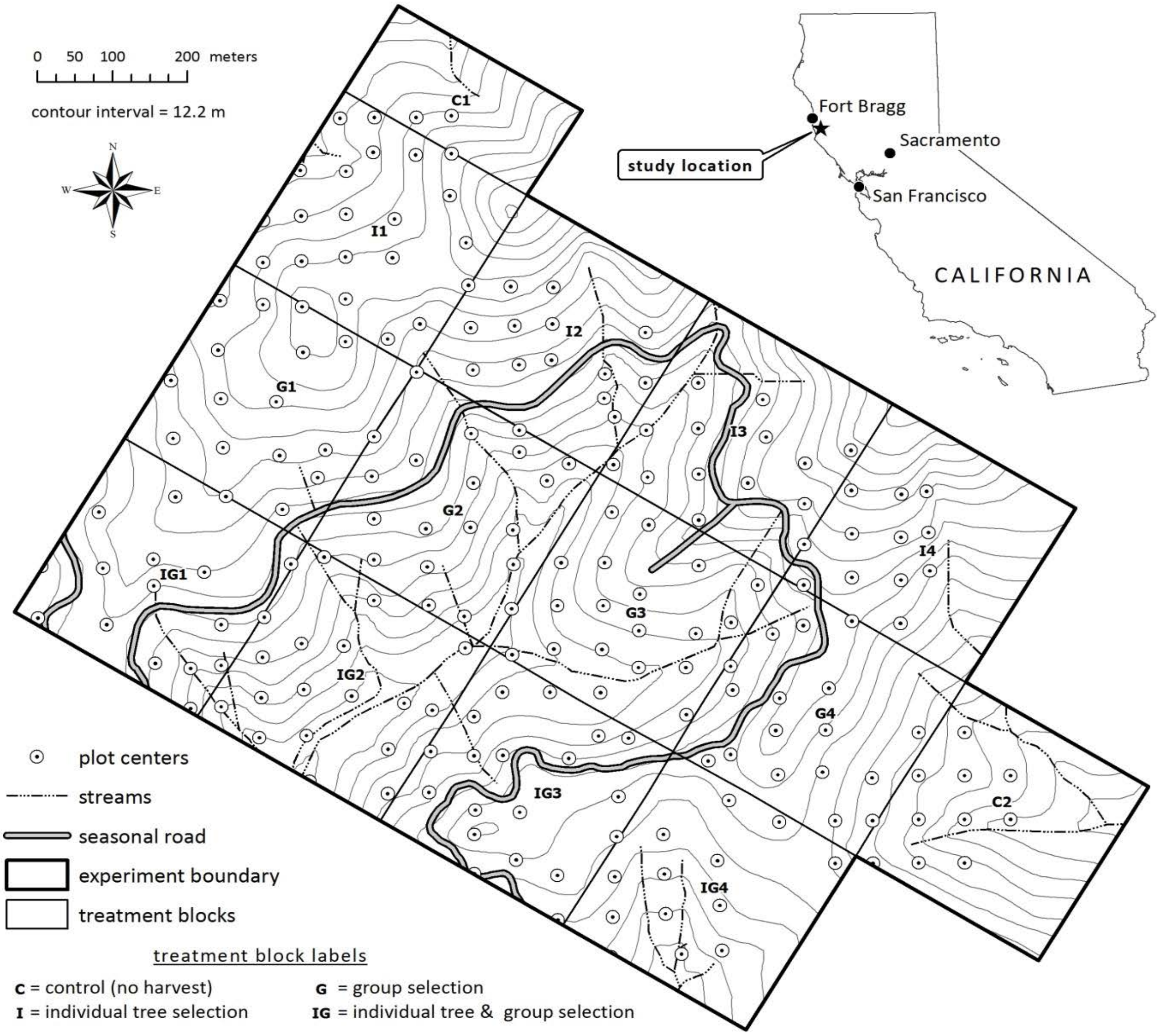

Figure 1: Topography, forest road, silvicultural treatments, and location of 0.04 ha permanent sample plots throughout 110-ha Railroad Gulch study area, Mendocino County, California, USA.

Spatial continuity in productivity

Omni-directional variograms developed using semi-variance data indicated that productivity index estimates in nearby plots were spatially correlated. Spherical models were selected to describe semi-variance for productivity indices (Figure 2). Range values signifying maximum distance of spatial continuity were lowest for redwood SI at 189 m, followed by 263 m for pre-harvest stand BA index. Greater spatial continuity was detected for post-harvest stand BAI index (311 m) and redwood BAI index (324 m), and for stand VI index (488 m) redwood VI index (466 m). Nugget effects (Y-intercept>0) were present for all variograms indicating that index estimates were affected by measurement errors and/or variability at small spatial scales. Overall, post-harvest stand VI index estimates were most variable between nearby plots (larger nugget effect) while having some degree of spatial continuity over longer distances (longer range) than SI or BAI index estimates (Figure 2).

Discussion

Sample variograms for productivity index estimates at Railroad Gulch depicted the extent of spatial autocorrelation, but also revealed high local variability in productivity between neighboring plots (nugget effect) (Figure 2). Site quality may be inherently variable at this site characterized by steep, variable terrain; however, this topography is common within the redwood range. We did not consider or test the impact of plot size on nugget effect. After partial harvesting in 1982, the 0.04-ha plots contained an average of 22 trees which is marginal when seeking precise estimates of BA and volume in stands with clumped elements such as redwood stump sprouts [27]. Localized variations may also relate to discontinuous sources of variability in site conditions such as changes in soil type or alterations to the hydrology from road building and associated flow diversion structures which are common in managed redwood forests. Partial harvesting under different prescriptions in each treatment

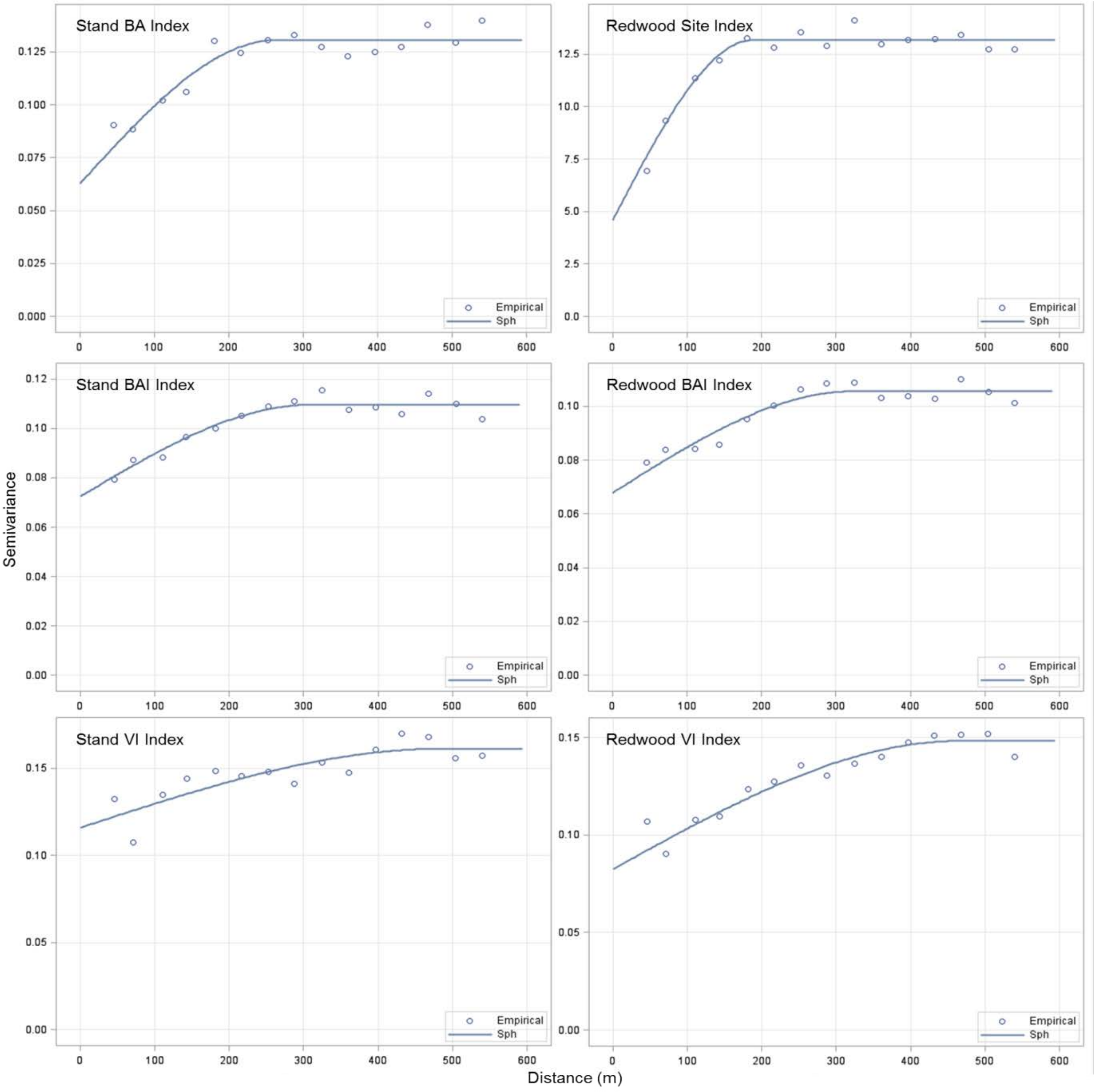

Figure 2: Spatial continuity of redwood forest productivity indices. Omni-directional empirical variograms and spherical (Sph) models for redwood site index and productivity indices for pre-harvest age-60 stand BA index and post-harvest basal area increment (BAI) index and volume increment (VI) index for stand (all species) and redwood component in 0.04 ha plots at Railroad Gulch, Mendocino County, California, USA.

block (Figure 1) created abrupt spatial changes in forest structure between blocks and within group selection treatment blocks. SI and the alternate indices of productivity were designed to be insensitive to differences in stand density between plots, so harvesting should not have contributed to local variability in productivity. The high degree of local variability presents challenges for researchers designing field experiments. For example, it may be difficult to find large areas of similar site quality to test different treatments. We expect localized variability in productivity to differ throughout redwood's natural range, and recommend developing sample variograms for different sites and regions. At Railroad Gulch we detected significant directional trends aligned with the major gully that bisected the study site (Figure 1). In general, productivity was more uniform across the slope and more variable up/downhill. This suggested that greater spatial continuity may exist within redwood stands located on more uniform topography and soils.

Longer ranges (i.e., spatial continuity over longer distances) in variograms for BAI and VI indices suggested that these may be more useful indicators of productivity than SI (Figure 2). Berrill and O'Hara presented multiple linear regressions indicating that BA productivity indices were consistently stronger predictors of stand and redwood VI than was SI [8]. Throughout redwood's natural range, variogram range for each productivity index may be affected differently by biophysical factors affecting tree- and stand growth such as variations in species composition, access to soil moisture, or exposure to wind which is known to impact height-diameter ratio in lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) radiata pine (*P. radiata* D. Don.), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) [28-31]. The restricted natural range of redwood apparently reflects a lower tolerance for drought and cold [28]. This may impart greater sensitivity to changes in growth-limiting resources such as soil moisture, resulting in greater variations in species composition, growth rates of individual species, and stand productivity at smaller spatial scales than other species and forest types. Redwood SI and our redwood component BAI and VI productivity indices were designed to mitigate the confounding influences of stand density and species composition, allowing us to reveal how development of dominant height, BA, and volume varied spatially according to differences in site quality. Therefore we would expect similar spatial continuity in productivity in pure or mixed redwood stands on similar terrain with similar climate. We can only speculate that productivity would be spatially autocorrelated over longer distances in the common forest types of other regions having less variability in site conditions and wider ecological amplitude of the dominant species.

At Railroad Gulch, covariance in productivity between neighbor plots decreased with increasing distance between plots. Productivity also exhibited variance between nearby plots, and was absent of spatial continuity beyond 200 m for SI and 300 m for BAI index within the 110-ha Railroad Gulch area characterized by heterogeneous topography and variable species composition. In theory, measuring SI in plots 200 m apart would maximize sample precision while preserving independence between samples. With this approach, a lower sampling intensity than with conventional site productivity estimation procedures would be needed to estimate the alternate indices of redwood forest productivity, BAI index, or VI index. VI index depends on accurate estimates of tree BAI and height growth which can be costly. Obtaining BAI index values involves either repeat measurements or shallow increment cores to obtain estimates of tree and stand BAI, which could be less time-consuming than bark-to-pith coring for SI and – unlike SI – can be calculated for even-aged and multiaged stands.

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