# Predicting Redwood Productivity Using Biophysical Data, Spatial Statistics and Site Quality Indices[1]

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### Abstract

Coast redwood (*Sequoia sempervirens* (D. Don) Endl.) height growth and basal area growth are sensitive to variations in site quality. Site factors known to be correlated with redwood stand growth and yield include topographic variables such as position on slope, exposure, and the composite variable: topographic relative moisture index. Species composition is also a key driver of redwood stand growth and yield. We studied spatial patterns in species composition in terms of percent hardwood, and spatial patterns in topographic relative moisture index values across 109 ha (270 ac) of coast redwood forest on Jackson Demonstration State Forest in Mendocino County, California. We also examined how redwood height growth (in terms of site index) and basal area productivity varied across the study area. We performed Ordinary Kriging in ArcGIS to interpolate between plots. These continuous raster data sets were used to create contour maps to assess redwood productivity in the study area. These example applications demonstrate a potential framework and method to estimate forest growth, yield, and carbon stocks in natural forests along gradients of productivity.

Keywords: GIS, interpolation, Kriging, semi-variance analysis, *Sequoia sempervirens*, uneven-aged, variogram

## Introduction

Combining forest inventory and remotely-sensed data offers opportunities to improve estimates of forest productivity and reduce sampling intensity and cost. To date, the potential for interpolation of measured and derived variables across forested land has not been widely studied or applied in regenerating mixed stands dominated by coast redwood (*Sequoia sempervirens* (D. Don) Endl.) in north coastal California.

Redwood is shade tolerant and long lived. Redwood height growth is sensitive to overhead shade (O'Hara and Berrill 2010). Unknowingly, foresters may sample dominant redwood trees for site index estimation that have undergone a period of height growth suppression. Site index estimates are also sensitive to measurement error, height growth prediction error, sample size, and method of calculating average height for the larger trees in the stand (Garcia 1998). Redwood site index can vary widely within stands; within a 109 ha (270 ac) stand the range of plot estimates for redwood site index diverged by a factor of two (i.e., range between 20.4 to 40.5 m (67 ft to 133 ft) at base age 50 years; Berrill and O'Hara 2014). Stand basal area and volume increment also vary in space, in large part due to variations in species composition. Focusing on one dominant species, we also find that redwood component basal area and volume increment also vary spatially according to differences in site quality not explained by site index (Berrill and O'Hara 2016). This inherent variability creates challenges for sampling and inventory, especially in managed stands further complicated by harvesting, growth, and regeneration which alter stand density, stand structure, and spatial patterns of tree locations.

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Sampling efficiency has been studied in redwood and other forest types. Sample precision increased as more redwood trees were sampled in fixed area plots (Berrill and O'Hara 2012). Markedly different sample sizes may be needed to achieve a specified level of accuracy or precision for different attributes or in stands with different tree sizes (Gray 2003). Berrill and O'Hara (2015) showed that redwood site index was more variable over short distances (<198 m or <650 ft) than other redwood productivity index variables. Their semi-variance analysis indicated that all indices of productivity were spatially auto-correlated but variable between nearby sample plots (i.e., at smaller spatial scales). Dominant redwood height growth lacked spatial continuity beyond 198 m (650 ft, 1/8 mile), indicating that estimates of site index from plots closer than 198 m apart would be spatially autocorrelated (i.e., plots were not independent samples). Basal area development in plots was spatially autocorrelated over greater distances within a study area with variable terrain and species composition (Berrill and O'Hara 2015). These findings suggest that estimates of redwood site index demand greater sampling intensity than sampling to index basal area or volume increment per hectare.

Understanding how productivity and associated biophysical variables vary in space will support design of efficient forest inventory and allow for improved calculation of stand totals for forest cover estimation and forest valuation for wood products or carbon offsets. The objective of our applied study was to demonstrate how sample estimates for key drivers of redwood stand growth and yield, and productivity estimates, varied spatially by mapping these variables in space by interpolation between known points on a sample grid.

## Methods

Our 109 ha (270 ac) study area at Railroad Gulch (latitude 39° 19′ 47″ N, longitude123° 41′ 50″ W) near the southwestern edge of Jackson Demonstration State Forest (JDSF), Mendocino, California, is covered by a grid of 234 0.04 ha (1/10 ac) sample plots. Tree measurements were summarized to give stand data, productivity, and site quality indices: redwood site index (Wensel and Krumland 1986) and redwood basal area index (BA Index; Berrill and O'Hara 2014). Species composition in each plot was calculated as percent of total BA (all species in plot) in the regenerating stand prior to partial harvesting in 1982. Redwood site index was calculated by averaging site index for four redwood trees of dominant or codominant crown class in each plot. The site index for each tree was calculated using tree height data and breast height age taken from bark-to-pith increment cores (Wensel and Krumland 1986). Redwood BA Index was calculated for each tenth-acre plot by comparing the redwood component BA (per unit area) to the average redwood component BA in all plots for that density (Berrill and O'Hara 2014). Biophysical data were collected in the field or derived from a 10 m digital elevation model (DEM) for each sample plot at Railroad Gulch (Berrill and O'Hara 2016). Topographic relative moisture index (TRMI) was calculated for each plot using field-based measurements of aspect, slope profile curvature, slope steepness, and position on slope (Parker 1982).

We developed semi-variograms depicting covariance between pairs of plots for estimates of percent hardwood, TRMI, redwood site index, and redwood BA Index (Isaaks and Srivastava 1989). Next we fitted spherical variogram models to each semi-variogram, and used the models for Ordinary Kriging interpolation of each variable across the entire study area. The interpolated data (i.e., Kriging means) were displayed as color contour maps with higher and lower levels of each variable depicting spatial patterns and variability.

## Results

Mapping the Kriging interpolation of percent hardwood indicated that hardwoods were more common on some, but not all, south-facing slopes and were concentrated in small- and large-sized patches (fig. 1). Hardwood-dominated sample plots that were surrounded by plots with a much lower hardwood component are depicted as a dark spot on the map of interpolated values. Conversely, a light-colored circle formed around plots without hardwood located in areas where most other plots had a hardwood component. Adjacent to these locations of unusually high or low hardwood percent, the interpolated values of hardwood percent changed rapidly over short distances from these plots with locally-dissimilar species composition.

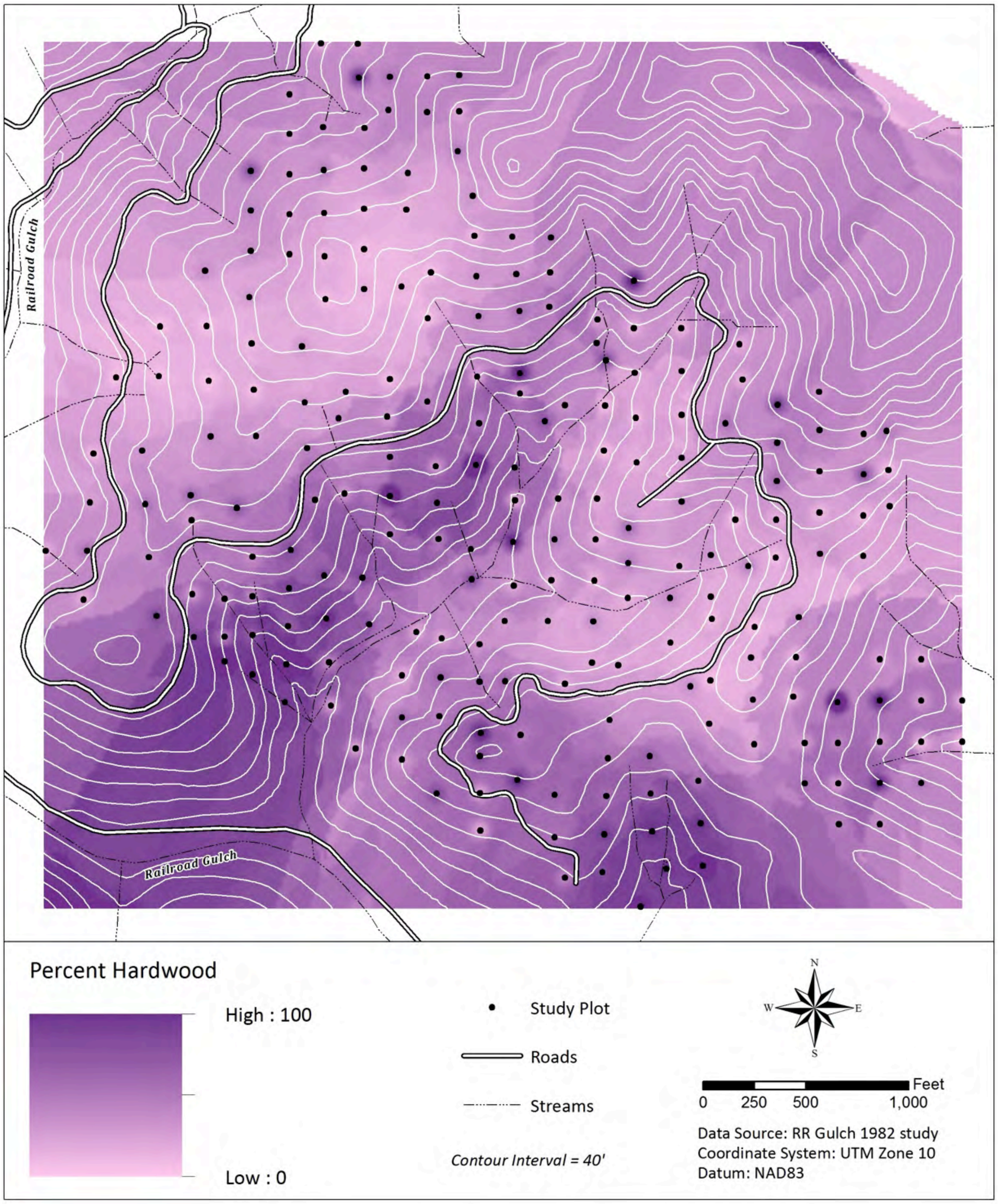


Figure 1—Kriging interpolation of species composition in terms of percent hardwood basal area in sample plots immediately prior to partial harvesting in 1982 at Railroad Gulch, Jackson Demonstration State Forest, Mendocino County, California.

Mapping the Kriging interpolation of plot estimates for TRMI showed how relative moisture related to topography across the Railroad Gulch study area. Topographic relative moisture index (TRMI) calculated for each plot using field-based measurements of aspect, slope profile curvature, slope steepness, and position on slope varied widely throughout the site, but did not exhibit high variability at smaller spatial scales (fig. 2).

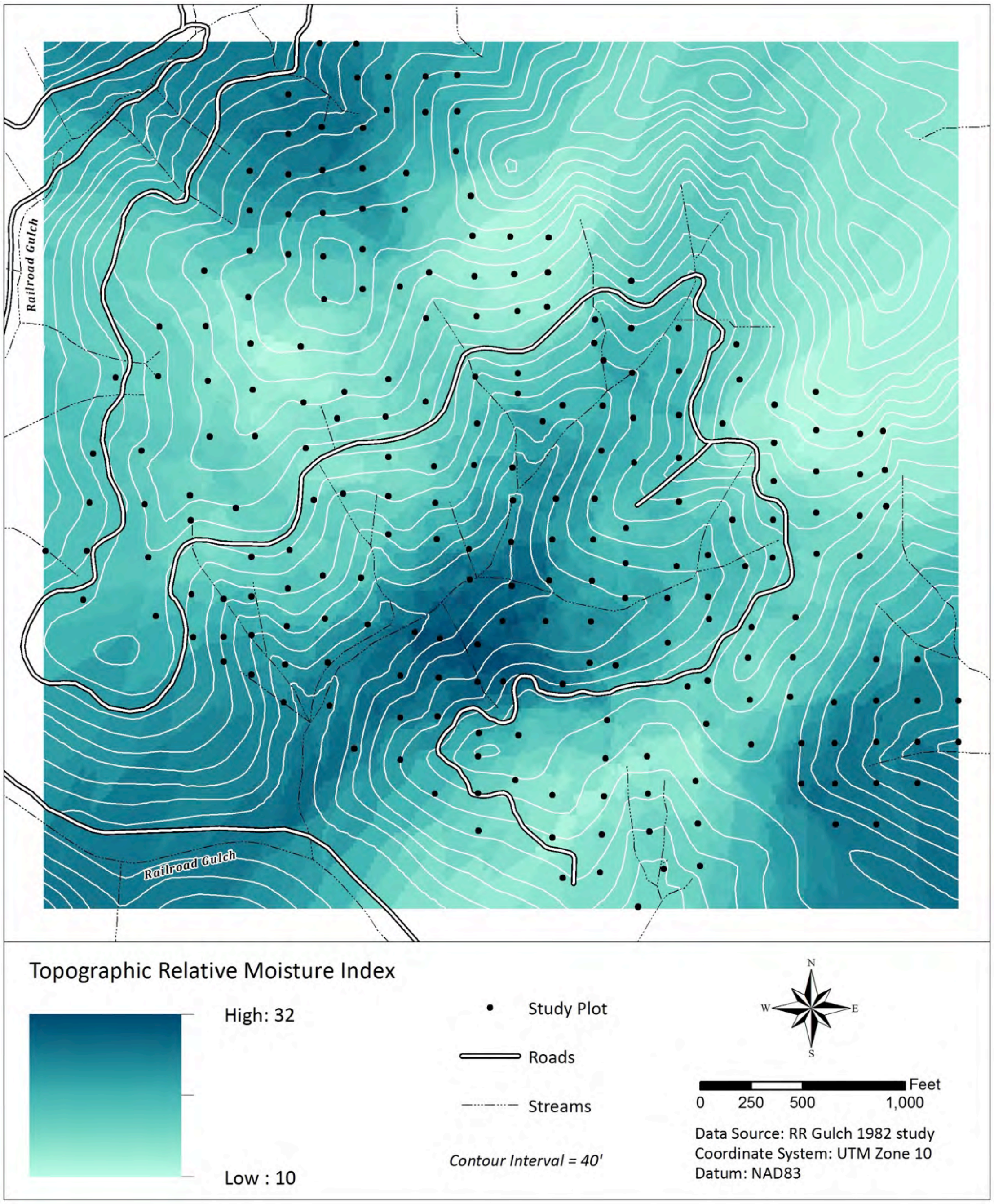


Figure 2—Kriging interpolation of topographic relative moisture index (TRMI) calculated for each plot at Railroad Gulch using field measurements of aspect, slope profile curvature, slope steepness, and position on slope (Parker 1982).

Redwood site index was strongly tied to topography, in particular the position on slope (i.e., gradient of ridge-upper slope-midslope-lower slope-gully). Site index was much lower in exposed ridgetop locations (fig. 3). Redwood BA development in each plot prior to partial harvesting in 1982 was indexed relative to the site-wide average BA per unit area for the redwood component in each sample plot. Kriging interpolation of the index values for BA Index in each plot (fig. 4) revealed that BA productivity did not necessarily coincide with high site index – itself a measure of redwood height development.

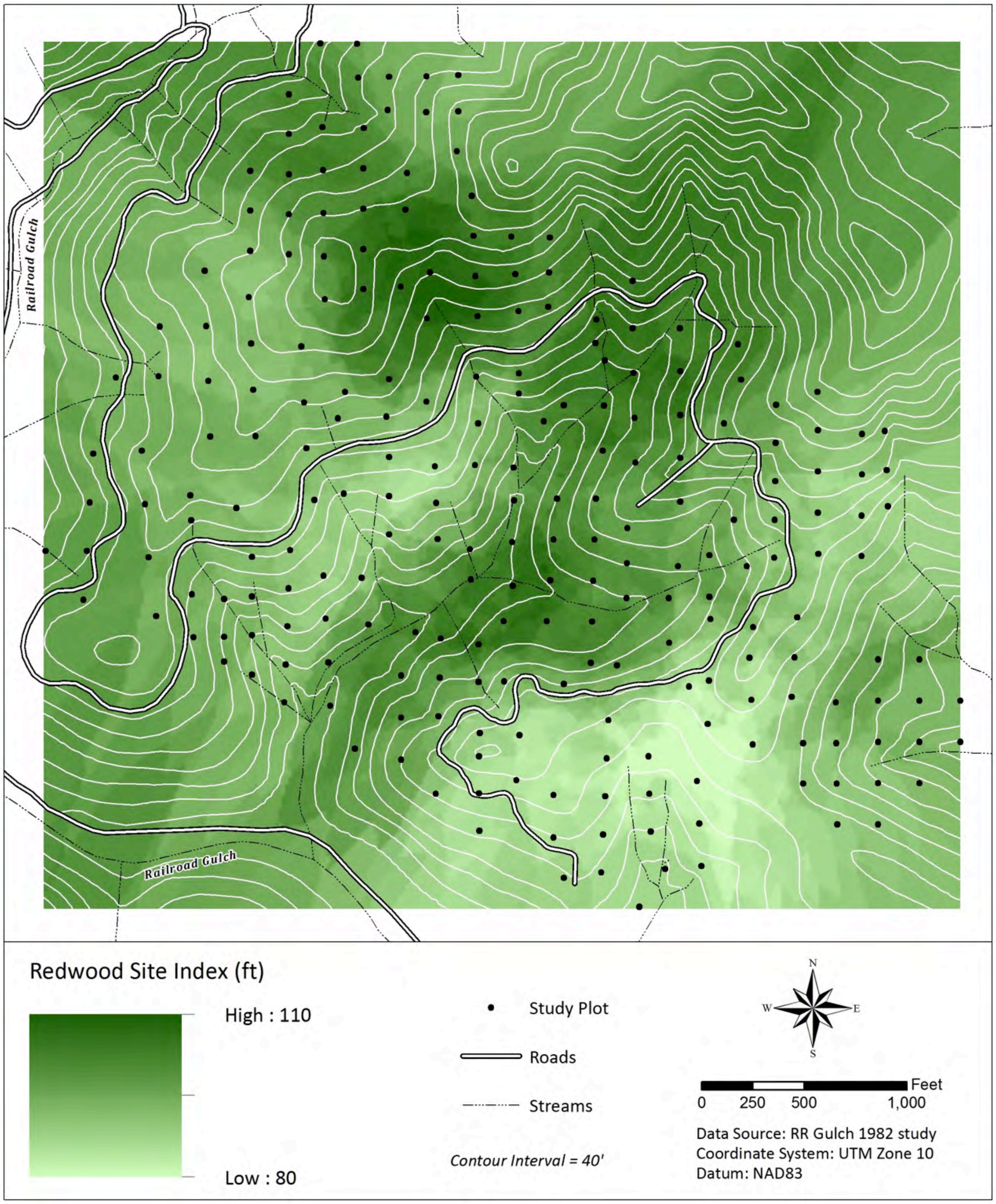


Figure 3—Kriging interpolation of redwood site index (base age 50 years) in sample plots at Railroad Gulch.

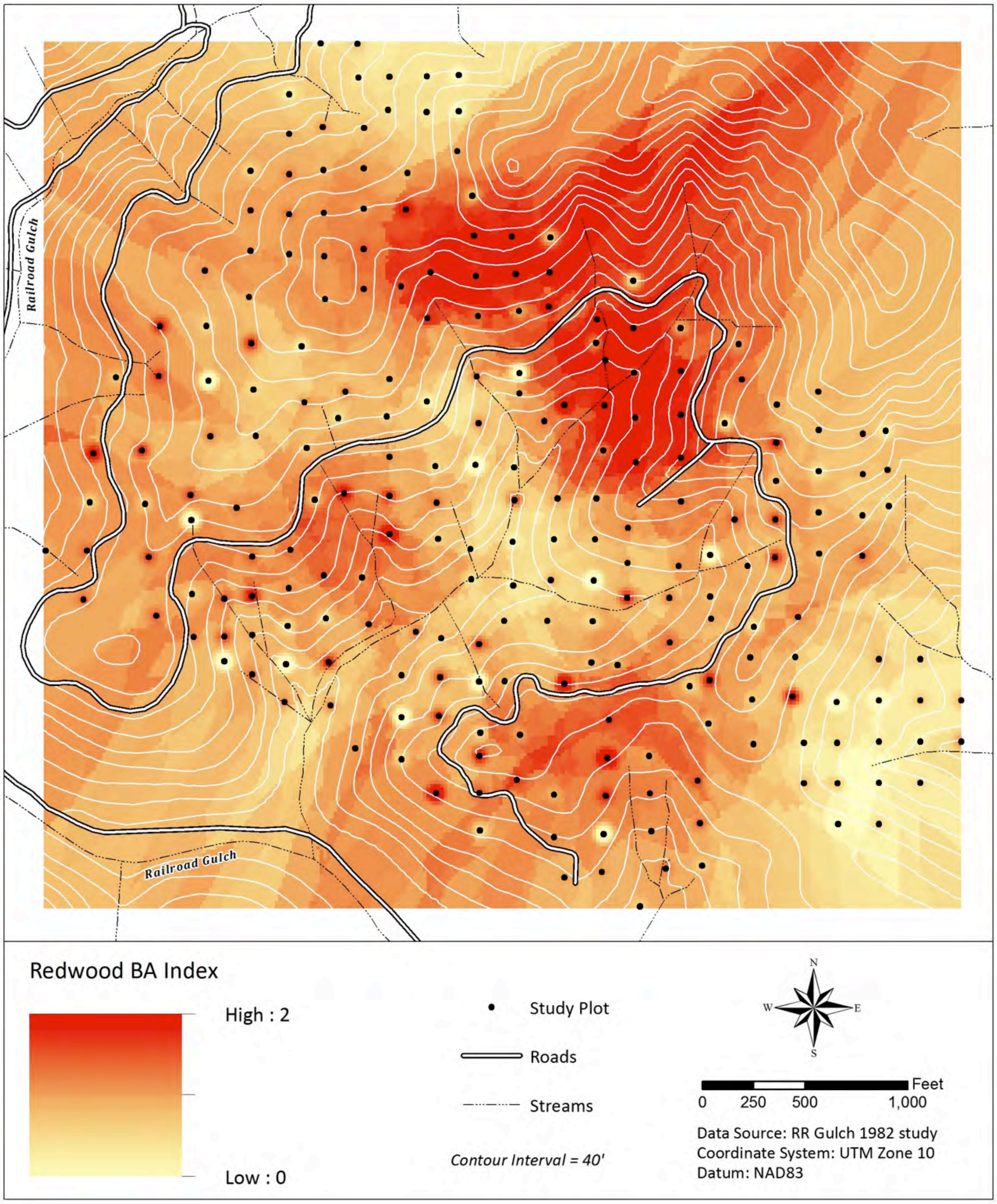


Figure 4—Kriging interpolation of redwood productivity in terms of pre-harvest age-60 redwood basal area index, the SDI-adjusted redwood basal area in sample plots immediately prior to partial harvesting at Railroad Gulch in 1982 relative the site-wide average redwood BA.

## Discussion

Variations in species composition (see fig. 1) were identified as the main source of variation in stand productivity at Railroad Gulch; areas with more hardwood were less productive, and areas with more Douglas-fir were more productive on a per-acre basis (Berrill and O'Hara 2016). Interpolation and mapping of species composition variables such as percent hardwood allows the forester to readily observe patterns across the landscape, stratify inventories, and design silvicultural prescriptions best suited to meet market demand and objectives of management in mixed stands.

The Kriging interpolation of percent hardwood revealed small patches of hardwood associated with a single sample plot, and larger patches of similar hardwood composition encompassing several neighboring plots (fig. 1). We were able to show these patterns and conclude that species composition is spatially heterogeneous because of our high density of sample plots. If one applied this interpolation technique between plots spaced further apart, larger patches of hardwood would be detected but smaller patches occurring outside sample plots would not be detected or shown. Basal area at age 60 was also spatially heterogeneous, varying widely between some adjacent plots (fig. 4). Presumably this related to many factors including species composition and site quality differences affecting BA growth, or insufficient plot size for sampling clumped tree spatial patterns (Berrill and O'Hara 2012), but may also be a reflection of localized disturbances and different rates and patterns of establishment affecting development of the regenerating second-growth stand.

Topographic relative moisture index (TRMI) was another important variable correlating with stand growth and per-acre growth of the redwood component at Railroad Gulch (Berrill and O'Hara 2016). The TRMI can be calculated using field-based measurements and assessments of slope variables and aspect, and then interpolated between known points. A more cost-efficient approach is to derive relative moisture indices directly from digital elevation models, especially for inaccessible/remote study areas and where high-quality DEM coverage is available. The TRMI is a composite index that integrates key topographic variables, such as position on slope, known to be correlated with redwood height growth and BA growth (Berrill and O'Hara 2016).

Other important corollaries with redwood growth can be derived from DEMs (e.g., topographic exposure; Quine and White 1998), remotely sensed via multispectral imagery (e.g., species composition), or taken from GIS map layers (e.g., geology and soil properties). Some of these variables correlate with either or both redwood height growth and redwood BA growth, which in turn vary widely at small spatial scales (Berrill and O'Hara 2014, 2015) and proceed somewhat independently presenting challenges for forest inventory and modeling (Berrill and O'Hara 2016).

## Conclusion

Kriging interpolation of key drivers of productivity and/or productivity index values gives a meaningful basis for estimating and summing stand growth and yield across any area with DEM coverage and interspersed with sample plots (or other data sources) giving species composition, tree- and stand data. Redwood forest managers and researchers are cautioned that forest growth and yield is highly variable at small spatial scales and that redwood site index cannot be expected to correlate well with stand BA and volume or the growth and yield of the redwood stand component.

## Literature Cited

**Berrill, J-P.; O'Hara, K.L. 2012.** Influence of tree spatial pattern and sample plot type and size on inventory estimates for leaf area index, stocking, and tree size parameters. In: Standiford, R.B.; Weller, T.J.; Piirto, D.D.; Stuart, J.D., tech. coords. Proceedings of coast redwood forests in a changing California: a symposium for scientists and managers. Gen. Tech. Rep. PSW-GTR-238. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 485–497.

**Berrill, J-P.; O'Hara, K.L. 2014.** Estimating site productivity in irregular stand structures by indexing basal area or volume increment of the dominant species. Canadian Journal of Forest Research. 44(1): 92–100.

**Berrill, J-P.; O'Hara, K.L. 2015.** Spatial variation in dominant height and basal area development in a coast redwood forest: implications for inventory and modeling. Biodiversity Management and Forestry. 4(4): 1–6. doi:10.4172/2327-4417.1000147.

**Berrill, J-P.; O'Hara, K.L. 2016.** How do biophysical factors contribute to height and basal area development in a mixed multiaged coast redwood stand? Forestry. 89: 170–181.

**Garcia, O. 1998.** Estimating top height with variable plot sizes. Canadian Journal of Forest Research. 28(10): 1509–1517.

**Gray, A. 2003.** Monitoring stand structure in mature coastal Douglas-fir forests: effect of plot size. Forest Ecology and Management. 175(1-3): 1–16.

**Isaaks, E.H.; Srivastava, R.M. 1989.** Applied geostatistics. New York: Oxford University Press Inc.

**O'Hara, K.L.; Berrill, J-P. 2010.** Dynamics of coast redwood sprout clump development in variable light environments. Journal of Forest Research. 15(2): 131–139.

**Parker, A.J. 1982.** The topographic relative moisture index: an approach to soil-moisture assessment in mountain terrain. Physical Geography. 3: 160–168.

**Quine, C.P.; White, I.M.S. 1998.** The potential of distance-limited topex in the prediction of site windiness. Forestry. 71: 325–332.

**Wensel, L.C.; Krumland, B. 1986.** A site index system for redwood and Douglas-fir in California's north coast forest. Hilgardia. 54(8): 1–14.